Environmental Remediation Group

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SENT VIA ELECTRONIC MAIL

July 06, 2018

Mr. James M. DiLorenzo
Superfund Project Manager
United States Environmental Protection Agency (USEPA)
EPA Region 1 – New England
5 Post Office Square (OSRR07-4),
Boston, MA 02109-3912

RE: Revised Rock Matrix Sampling Work Plan
Response to Comments dated May 22, 2018
Olin Chemical Superfund Site (OCSS), Wilmington, MA

Dear Mr. Dilorenzo:

Transmitted herewith is the revised Rock Matrix Work Plan for the Olin Chemical Superfund Site (OCSS), Wilmington, MA. The revised work plan incorporates relevant USEPA comments dated May 22, 2018 as well as items discussed during the June 14, 2018 conference call between USEPA, the Massachusetts Department of Environmental Protection, and Olin representatives. Olin's response to individual comments are also included as an attachment in the Work Plan. Note, the items requested on the June 14 call were previously submitted to USEPA on June 26.

Olin will plan to implement the work in a timely fashion following USEPA's approval of the revised work plan, as Olin has obtained relevant access to install the boring at the proposed location.

If USEPA or its representatives have any additional questions or comments on the submittal, Olin is available to setup a conference call to discuss and/or clarify details.

Sincerely,

OLIN CORPORATION

James M. Cashwell
Director, Environmental Remediation

Enclosure

cc: Garry Waldeck (MassDEP)
Chinny Esakkiperumal (Olin)
Michael J. Murphy (Wood)
Peter Thompson (Wood)

ROCK MATRIX SAMPLING WORK PLAN
OPERABLE UNIT 3
OLIN CHEMICAL SUPERFUND SITE
WILMINGTON, MASSACHUSETTS

Prepared for:

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Prepared by:

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Project No. 6107180016.007

July 6, 2018

Peter Thompson
Project Manager

Michael J. Murphy
Project Principal

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1.0 INTRODUCTION

This work plan has been prepared by Wood Environment & Infrastructure Solutions (Wood) for Olin Corporation (Olin) to conduct additional characterization for Operable Unit 3 (OU3) at the Olin Chemical Superfund Site (OCSS) in Wilmington, Massachusetts. This work plan provides discussion of the purpose and technical approach for collection of data to determine the presence and concentration of N-nitrosodimethylamine (NDMA) in the bedrock matrix immediately adjacent to the Main Street Dense Aqueous Phase Liquid (DAPL) pool (Figure 1). The work plan has been revised to address comments by the United States Environmental Protection Agency (USEPA) dated May 22, 2018 as well as the items discussed during a June 14, 2018 conference call between USEPA and Olin, regarding an earlier draft work plan that was submitted to USEPA on April 26, 2018. Olin's response to comments are provided in Attachment A.

2.0 PROBLEM STATEMENT AND OBJECTIVES

2.1 Background

In 2013, the Water Science and Technology Board (WTSB) of the National Research Council concluded that "*At least 126,000 sites across the country have been documented that have residual contamination at levels preventing them from reaching closure*" (WSTB, 2013). Despite over four decades of intensive efforts, the Board further acknowledges that reducing anthropogenic contaminants to levels that allow limited or unrestricted exposure to such groundwater remains a significant technical and institutional challenge. This is especially true for sites that are technically complex from a hydrogeological and contaminant perspective even though those sites only comprise an estimated 10% of the outstanding 126,000 sites posing significant technical challenges to remediation of groundwater.

The Board further concludes that "*Although there is no formal definition of complexity, most remediation professionals agree that attributes include aerially extensive groundwater contamination, heterogeneous geology, large releases and/or source zones, multiple and/or recalcitrant contaminants, heterogeneous contaminant distribution in the subsurface, and long time frames since releases occurred. Additional factors that contribute to complexity include restrictions on the physical placement or operation of remedial technologies and challenging expectations (e.g., regulatory requirements, clean-up goals, community expectations). The complexity of a site increases with the number of these characteristics present. Fractured media are often considered the most heterogeneous and limit the effectiveness of remedial technologies*".

In recognition of these well-established limitations to groundwater restoration, the U.S. Department of Defense (DoD) through the Environmental Security Technology Certification Program (ESTCP), developed a study that discussed the long-term necessity for alternative endpoints and approaches for sites with "*underlying technical limitations to groundwater cleanup*." In this document, (Deeb, et. al., 2011) DoD identifies that at sites with fractured bedrock settings, matrix diffusion and matrix storage of contaminant mass can lead to long extended cleanup timeframes. The importance of matrix processes on the fate of contaminants has been well established for over two decades and has been discussed by numerous authors including Pankow and Cherry, 1996; and Parker et al, 1997; as well as the detailed site characterization and evaluation approach and protocols for assessment and evaluation of matrix diffusion in Discrete Fracture Networks (DFN) (Parker, 2007). The DFN approach focuses on detailed characterization of borehole hydraulics and groundwater and rock matrix contaminant distribution.

As discussed during the June 14 call, the DFN approach is neither new nor innovative. The DFN approach is a synthesis of previously published articles on technologies related to the investigation of contamination in fractured and fractured porous media, discrete interval monitoring, solute transport and groundwater modeling. The DFN approach articulates a systematic methodology for the characterization of fractured sedimentary bedrock that is transferable to other bedrock types, specifically metamorphosed sedimentary rocks. The primary elements of the approach include continuous coring of bedrock, crushing and analysis of rock core, borehole geophysics, straddle packer testing, partitioning calculations, and numerical modelling. A different approach for fractured bedrock is necessary because diffusive chemical mass transfer relocates contaminant mass from the active fractures into low permeability matrix blocks between the fractures. The first application of the DFN approach by Parker was in 1996 at a chlorinated solvent site in the Simi Valley of California within a sandstone – shale sequence. This is contemporaneous with similar fractured bedrock characterization approaches developed by Wood (formerly ABB Environmental Services [ABB-ES] and Harding Lawson Associates [HLA]) at the Quarry and Entomology Shop Sites at former Loring Air Force Base (ABB-ES, 1997 and HLA 1998 and 1999), subsequent work by USEPA at the Quarry Site (EPA, 2005), and site characterization at the Eastland Woolen Mill Site in Corinna, Maine (HLA,-2004) , As new technologies become readily accepted they may be incorporated into the DFN methodology; such examples have included FLUTe liner systems, and high resolution temperature logging.

2.2 Problem Statement

Numerical proof of concept fate and transport modelling has been conducted for the OCSS to quantitatively illustrate the effects of matrix diffusion and advective matrix transport of NDMA. The results of modeling indicate extremely long time frames (well in excess of 300 years) would be required to remediate fractured bedrock groundwater that has been in contact with high concentrations of dissolved NDMA for a long time, such as the diffuse groundwater under and down gradient of the Main Street DAPL pool within the Ipswich watershed.

From a conceptual standpoint the fractured rock - matrix system typically includes a dominant set of fractures with several different orientations that cross connect and provide hydraulic continuity across the bedrock system. This allows groundwater to move in response to hydraulic head (gradients) but the predominant movement is controlled by connected fractures as well as fracture orientations. Over a representative volume of the aquifer, these systems are generally conceptualized and evaluated to behave approximately like an equivalent porous media (EPM). The intervening blocks of bedrock defined by the intersection of these major fracture sets are not monolithic and are commonly weakly fractured based on current borehole logging information. The weakly fractured bedrock and the hydraulically dominant fractures are connected and are both in intimate contact with the adjacent, un-fractured, rock matrix.

Matrix diffusion is one of the primary physical processes that transfers dissolved constituents from secondary porosity features (such as faults and fractures) into the adjacent primary rock matrix porosity by chemical diffusion. Diffusion is usually described by Fick's first law relating the chemical's diffusion coefficient to distance and time. Diffusion occurs in response to a contaminant concentration gradient between the secondary and primary porosity. NDMA has a reported diffusion coefficient of 0.84 cm^2d^{-1} (GSI Chemical Data Base. https://www.gsi-net.com/en/publications/gsi-chemical-database/single/404-nitrosodimethylamine-n.html), which based on Fick's

Law yields a migration distance of approximately 6 feet by diffusion processes over a 60 year period (the approximate time the DAPL pool has been present). Back diffusion is the process in reverse which occurs once the secondary porosity concentrations in fractures decline (due to flushing) to a level lower than within the adjoining primary rock matrix porosity. However even as back diffusion begins to reverse the direction of contaminant migration, the process of diffusion within the rock matrix continues unabated due to interior concentration gradients. This greatly extends the time period over which back diffusion occurs. Hence, to understand and estimate groundwater remedy duration, it is critical to estimate and/or quantify the contamination in rock matrix.

Advection under low hydraulic conductivities is also an important transport process both in the rock matrix and the weakly fractured bedrock. Modeling indicated advective transport was an important fate and transport process for this media. During characterization of dissolved phase groundwater impacts in fractured bedrock, much emphasis is placed on identification and monitoring of the individual fractures that dominate the flow or movement of water within an individual borehole (the dominant or transmissive fractures). The most transmissive fractures are typically sampled and monitored by installation of screened intervals and multilevel devices to understand the bulk contaminated groundwater movement in bedrock. These approaches do not consider the potential long-term importance of intervening weakly fractured bedrock as a contaminant storage reservoir that is part of the fabric of the bedrock system. Both the major dominant fractures and the weak fractures are adjacent to un-fractured rock matrix. For convenience we shall simply refer to this as the bedrock fracture-matrix structure. The weakly fractured bedrock, is typically not studied since these types of fractures do not yield sufficient quantities of water to allow sampling by conventional means. These zones of weakly fractured bedrock not only intersect the boreholes where studied but also the fracture planes where the bulk of groundwater is transmitted. It is unknown whether the rock matrix adjacent to these weak fractures, or within the weakly fractured zones, is also impacted by diffusion to a degree that would contribute to the long-term retention of contaminant mass in the groundwater system. If the weakly fractured or low transmissivity bedrock in fact contains high dissolved concentrations of NDMA, then the rock matrix adjacent to those fractures is likely impacted as well.

Such complex bedrock geology and hydrogeology is observed near the area of interest. The borehole geophysical log from GW-406BR located east of Jewel Drive provides a good example. The nature of this borehole is similar to the data obtained from SB-8/MP-4 that was drilled in the Main Street Bedrock Saddle, approximately 120 feet west of the proposed test location. The GW-406BR borehole log indicated three likely transmissive and one possible transmissive fractures or zones based on Heat Pulse Flow Meter (HPFM), Acoustic Televiewer (ATV), optical, caliper and electric logs. These four fractures clearly dominate the hydraulics of the borehole based on HPFM data; however inspection of the calliper, ATV and optical logs reveals that more than 30 additional fractures are present, many very fine in character, others more conspicuous. All these additional fractures in addition to the four main transmissive fractures could be an integral part of the chemical mass storage behaviour of this bedrock. **Figure 2** illustrates these types of features within GW-406BR. This type of fracturing is not uncommon and has been observed at other contaminated fractured bedrock sites in New England (for example the Eastland Woolen Mill Superfund Site No MED980915474)[1]. Micro fractures are also typically present on a scale smaller than can be

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[1] At the Eastland Woolen Mill Superfund Site, for example, similar results were apparent from detailed characterization of source area fractured bedrock using similar methods. Several hundred fractures were identified that were low transmissivity, yet the hydraulics of the groundwater system under pumping conditions was dominated by fewer than 10 fractures, especially lower angle fractures that cross connected the more common

discerned by borehole geophysics. Hence, it is critical to understand the behaviour of groundwater hydrology and fate of contaminants not only in interconnected fracture system in the intervening weakly fractured bedrock but also in rock matrix adjacent to these fractures.

2.3 Objective

The overall objective of the proposed boring location (shown in **Figure 1**) is to verify conclusions of the numerical modeling, as suggested by USEPA during a technical meeting on February 7-8, 2018, by conducting rock matrix sampling at a location known to have high concentrations of NDMA in groundwater, and that has fracture characteristics of the geology near the Main Street DAPL pool. The preliminary conceptual 2-Dimensional (2-D) modeling to simulate the expected fate and transport of NDMA in fractured bedrock was based on data associated with the Main Street DAPL pool. The model indicated both matrix diffusion and advective transport through low hydraulic conductivity bedrock are expected to contribute to recalcitrant, long term impacts to bedrock groundwater. The results of the model were previously provided to USEPA (e.g., February 7-8, 2018 technical meeting between USEPA and Olin).

This work plan addresses installation of a borehole and proposes investigation methods that accomplish the following specific objectives:

- Verify whether NDMA is present in rock matrix adjacent to fractures through which NDMA-impacted groundwater is being transmitted at the borehole location;
- Quantifying NDMA presence, concentration and mass, if feasible, in bedrock adjacent to fractures in the borehole;
- Evaluating the distance at which NDMA can be detected in rock matrix from an identified fracture in the borehole;
- Developing a refined conceptual model of the frequency and vertical extent of NDMA impacts to the bedrock matrix in the borehole;
- Measuring dissolved NDMA concentrations in groundwater in dominant transmissive fractures in the borehole,
- Measuring NDMA concentrations in groundwater in weakly fractured bedrock in the borehole.
- Characterizing transmissivity of the entire borehole so that zones of low transmissivity can be identified and related to specific fracture features in the borehole, and
- Adapting and implementing commercially available methods (e.g., FLUTe liners) to sample and characterize groundwater in low transmissivity bedrock zones.

The second to last bullet above bears special discussion. As pointed out by Neuman (Neuman, 2005), where the volume of rock under study is dominated by just a few fractures, the detailed study of bulk aquifer properties

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bedding plane fracture sets. That source area was documented to have extensive matrix impacts from diffusion of chlorinated benzene compounds which have diffusion coefficients similar to NDMA.

(permeability, transmissivity, etc) often result in sharp and wide variability that is not easily interpreted. In order to better understand flow and consequently contaminant transport at a smaller scale in DFNs, testing of aquifer properties should be conducted with high spatial resolution where deemed economically and technically feasible. In 2014, Keller (Keller, Cherry and Parker, 2014) published a new approach for continuous measurement of transmissivity in bedrock boreholes which provides a high spatial resolution of borehole transmissivity. This method is one of the technologies referenced by Parker as part of the DFN approach (Parker, 2012).

The proposed borehole location in this Work Plan was based on existing data from the Main Street Bedrock Saddle Investigation and in particular boring SB-8 that was completed as multi-level piezometer MP-4. The proposed location was selected as near as possible (approximately 160 feet) to existing multi-level piezometer MP-4 without infringing on private residential property. The MP-4 location is well characterized and the data indicate bedrock on the down gradient side of the Main Street DAPL Pool, is located down dip along fractures which are oriented toward and under the western side of the Main Street DAPL pool. The Remedial Investigation data indicated high concentrations of NDMA are present and the data from this area was used in developing the conceptual numerical model. The proposed location is, like MP-4, on the downgradient side of the DAPL pool and in a down dip direction of fractures oriented toward and under the DAPL pool. Details of the characterization effort that defined the Main Street Bedrock Saddle are contained in Geomega Technical Report Series XVII (Geomega, 2001) which was discussed and provided to USEPA previously as part of the Focused RI Report (MACTEC, 2009) and contained in Appendix A of the Draft DAPL Focused RI Report (Amec Foster Wheeler, 2017).

MP-4 underwent an extensive characterization consisting of hydraulic packer tests, borehole geophysical logging, and hydrophysical logging performed in the bedrock portion of the boring to determine fracture density and orientation and the hydraulic conductivity of transmissive fracture zones. As previously mentioned, data from SB-8 and MP-4 and numerical model results have been previously submitted to USEPA.

3.0 TECHNICAL APPROACH

The technical approach to this work includes installing the proposed boring using standard rock core methods, processing of core samples for matrix extraction and chemical analysis, and characterizing the transmissivity of the borehole. The proposed approach in general follows the protocol outlined in the 2009 approved RI/FS Work Plan for the Site.

3.1 Bedrock Coring, Rock Matrix Sampling and Analysis

Borings will be advanced into bedrock with five-foot-long core barrels. The core will be processed at one-foot intervals by crushing the core; and samples of the crushed rock will be collected, preserved, and prepared for laboratory analysis. At the laboratory, samples will be extracted and the extracts will be analyzed for NDMA. Details of coring, sampling, and lab analysis are provided below.

3.1.1 Bedrock Coring, Sample Selection and Preparation

Bedrock will be cored using conventional coring methods. A nine-inch (9") diameter casing will be sonically advanced to the top of bedrock and into bedrock to set the casing at a depth where both the driller and Wood geologist determine to be sufficiently competent to grout a casing in place. At that terminal depth, a six-inch diameter permanent steel casing will be installed and tremie-grouted to grade. Following curing, the borehole will be cored to an additional 150 feet into bedrock, using HQ wireline coring techniques using five-foot length triple tube core barrels. The core from the nine-inch diameter sonic drilling will be logged and evaluated for processing in the same matter as the HQ core. Core will be logged and documented in field data records consistent with the approved RI/Feasibility Study (FS) Work Plan (MACTEC, 2009).

Samples of the core will be collected and processed for extraction and chemical analysis as discussed in subsequent sections. The field geologist (from Wood) will select the core samples to be processed as discussed below. The subcontractor uses proprietary equipment to crush the rock core and transfer the crushed sample to the sample container with minimal exposure to atmosphere. All core samples will be prepared for laboratory analysis on site, including, crushing and preservation in provided glassware. Other routine field activities (e.g., Quality Analysis [/ Quality Control samples at 20% frequency, field duplicates, record keeping, database management, and decontamination), will be performed as outlined in the approved 2009 Work Plan. Data collected will include sample jar tare weight, and combined sample container rock weight so the rock sample weight may be determined by subtraction. Sample weights will be recorded on field data records and recorded on the sample label and along with sample ID, time and date of collection.

Samples will be selected at specific distances from identified water bearing fractures (natural fractures). Core from each five-foot run will be laid out in a core box and fit together accommodating mechanical breaks and natural fractures. Natural fractures will be identified based on surface appearance (weathering, presence of iron oxides, alteration). The core length recovered will be measured and recorded and the length of un-fractured rock cores between or adjacent to natural fractures will be estimated and recorded. Measurements to calculate Rock Quality Designation (RQDs) will be made. For reference, during advancement of SB-8/MP-4, the overall RQD was approximately 50%, indicating that 50% of the core recovered was in lengths less than 4 inches.

The core samples will be selected to target rock matrix adjacent to and at measured distances from dominant water bearing fractures and adjacent to and at distances from weak fractures within the weakly fractured bedrock. **Figures 2 and 3** show examples of how such a sampling approach might be deployed using the borehole log from GW-406BR as a surrogate. **Figure 4** provides a generic decision tree as guidance to help explain the sampling process. The actual samples to be collected will be decided in the field based on available core and professional judgement – however, the sample collection will follow these guidance. In addition to the decision tree given in **Figure 4**, below are some other general field guidelines:

- If a five-foot core run is not fractured, it will be evaluated in conjunction with the adjacent cores from the prior and subsequent runs.
- If several adjacent sequential core runs are un-fractured, a minimum of one sample will be collected from each five-foot core run.
- If weathered rock matrix is encountered, it will also be sampled in accordance with the frequencies described in the decision tree.

Up to four representative core specimens will be collected for physical characterization at an off-site accredited laboratory. Physical characterization will include density, porosity, and fraction of organic carbon.

3.1.2 Sample Collection and Preservation

Approximately 100 grams of crushed rock will be collected and added to a pre-weighed sample jar. An amber 250 milliliter jar, routinely used by the laboratory for soil samples, will be used for the crushed rock. Rock samples will be added to sample jars and shipped directly to the laboratory. NDMA is not substantively volatile and the rock samples will be preserved on ice at 2 - 4 degrees C as specified for semivolatile organics soil samples. Samples will be shipped on a daily basis and extracted and analyzed at the laboratory as described below. The extraction will commence within 48 hours of laboratory receipt of the samples.

3.1.3 Sample Extraction and Analysis

Several extraction approaches, both in-field and in-laboratory were considered during development of this work plan, including possible use of microwave extraction, deionized water, methanol, and methylene chloride. For consistency with analytical methods that are used for NDMA in other media and for worker safety, extraction will be conducted in the laboratory (TestAmerica) using the same extraction method and solvent used for soils.

Extracts from bedrock core samples will be analyzed for NDMA using a low detection limit procedure for NDMA (lowest possible detection limits) in accordance with TestAmerica Sacramento modified Method 521 SOP WS-MS-0012. The extraction method will be modified for rock chips to increase the time that the rock matrix is exposed to solvent. The primary goal of the sampling event and analysis method is to determine the total concentration of NDMA in the rock matrix to evaluate the retention of NDMA in the bedrock media.

This rock method was designed to keep the analytical procedures as close as possible to the routine procedures currently in use at the laboratory as a way of obtaining the most reliable analytical data.

Labelled isotope internal standard NDMA-D6 will be added to the solid matrix prior to adding the extraction solvent. The need for use of a drying agent (sodium sulfate or equivalent) will be determined by the laboratory based on the characteristic of the crushed rock media. If moisture is observed in the sample, the drying agent will be applied and stirred into the rock using similar procedures as is done for soil samples. Based on the expected character of the samples, this is not expected to be a common occurrence. The laboratory will add the extraction solvent dichloromethane (methylene chloride) to the rock chip samples. The sample will be covered and stored in a dark location for two weeks (14 days). After 14 days, sample extraction for the rock chips will continue using sonication USEPA Method 3550. Sonic horns are set up for each individual sample using the same 250 ml jar used to collect samples following the same procedure as soils. The solvent from the first sonication will be stored in a capped flask or beaker. Extraction involves three sonication events with new solvent added for each event. After the first sonication volume, a second volume of solvent is added and the sample is allowed to sit for one week (7 days) and then the second sonication is completed. This step is repeated by adding the third aliquot of solvent, allowing it to sit for one week, and then completing the last sonication. Solvent from the three sonication steps is combined prior to concentration and analysis. The concentrated extracts will be analyzed by the laboratory within 40 days of the initiation of the extraction as specified in the analytical method. The total duration of the extraction period will be approximately four weeks. Samples will be stored and extracted during this time in a darkened environment at normal room temperatures to minimize exposure to ultraviolet radiation which is known to degrade NDMA.

<u>Selection of Samples to be Analyzed</u>

Not all samples that are collected, processed, and extracted will be analyzed. The extracts will have a 40 day hold time consistent with the current NDMA method (modified 521). Initially a subset of samples will be selected for an initial phase of chemical analysis based on field observations and data (fracture type and water bearing characteristics, associated packer sample results, distance from a fracture or fractures, borehole geophysical logging etc). It is currently anticipated that this first phase of samples analyzed will be approximately 30-40% of the total sample group. The exact amount of samples to be analysed during first phase of analysis will be determined in the field, which will be focused on locations in proximity to fractures. Based on the preliminary results from these analyses, additional extracts may be selected for analysis, as appropriate.

Extended Re-extraction Samples

A subset of samples will be selected for re-extraction using an extended extraction time to determine if additional residual NDMA is subsequently extracted from samples following the original extraction and analysis. Another aliquot of labelled isotope internal standard NDMA-D6 and methylene chloride will be added to the sample when the initial extraction is completed. Samples will be stored for a period of approximately 2 weeks. At that time, sample extraction will continue following the routine extraction procedures normally followed by the laboratory for Method 3550. The results from the re-extracted samples will be used to evaluate the retention of NDMA in the rock matrix and provide an assessment of the effectiveness of the initial extraction procedure.

3.2 Borehole Structure and Hydraulic Characterization

The borehole will be geophysically logged consistent with Addendum IV to the RI/FS Work Plan (MACTEC, 2010). In fractured environments, groundwater velocities in fractures can be quite high especially due to increased borehole heads caused by drilling. The amount of water used in drilling the borehole will be recorded by the field geologist in the field logbook. The borehole will be developed to the point where water is not occluded and generally clear to the eye. The purpose of this is to provide a suitable borehole environment for conducting borehole logging.

Following borehole logging, packer samples will be collected from the dominant, hydraulically active fractures identified by borehole geophysical logging. Since we expect that these fractures, undisturbed, would have been occupied by diffuse groundwater, monitoring specific conductivity will provide a good indication if these groundwater samples are generally representative of impacted zones. These samples will be submitted for off-site analysis for NDMA, sulfate, chloride, ammonia, magnesium and sodium. The cations and anions will be used to estimate specific gravity of the fluid. Field parameters (specific conductivity, oxidation – reduction potential, dissolved oxygen, temperature and pH) will be recorded for purge water and final samples. These NDMA results will be considered as screening level data, since there will only be limited time for the borehole to re-equilibrate after drilling. Packer sampling will be conducted consistent with Appendix IV of the RI/FS Work Plan. These procedures may require modification for monitoring heads during testing, as necessitated by a small packer assembly and set-up. Subsequent to logging and packer sampling, a blank FLUTe liner will be everted down the borehole and using FLUTe's continuous Transmissivity Profiler, a continuous profile of borehole transmissivity will be developed. This will also serve to seal the open borehole while the borehole, packer, and transmissivity data is being analysed.

Results from the borehole logging, initial packer sampling, and the FLUTe continuous transmissivity profile will be used to evaluate and identify zones for monitoring with a FLUTe multilevel system customized for that borehole.

3.3 Low Transmissivity Bedrock Groundwater Sampling and Analysis

A FLUTe liner multilevel system will be installed (adapted from existing technologies) to monitor low transmissivity fracture networks identified by borehole logging and the transmissivity profiler to supplement the high transmissivity fracture sampling conducted with straddle packers. Up to 4 zones (ports) can be constructed in a liner for the diameter of an HQ core hole. Monitoring of the low transmissivity zone will be conducted by modification of the FLUTe liner system. These modifications have been discussed with FLUTe. The design of the system will be discussed with USEPA prior to fabrication. The FLUTe system will be modified to work in a manner analogous to a suction lysimeter, which applies a slight vacuum over an extended period of time to induce flow into the sample chamber. In essence what is proposed is development of a bedrock suction lysimeter to induce flow from the weakly fractured bedrock system into the port of the FLUTe liner. Since this type of system has not been developed and implemented previously, operation of the system will be based on an observational method. Depending on the transmissivity of the fractures monitored, we envision a vacuum would be applied over a duration of hours up to several days. Rather than allowing the water to flow in by gravity, flow will be induced by a negative pressure. It may be necessary to cycle the system between negative and atmospheric pressure conditions to obtain sample volumes required for analysis. Samples will be purged from the system by an inert gas consistent with normal FLUTe sampling procedures. Samples will be analysed for NDMA. The Flute design can also be adapted to monitor both low transmissivity zones and transmissive Fractures as shown in **Figure 5**.

It is anticipated that once installed, the FLUTe system will remain in place until the objectives for this work are met and additional data is no longer needed. These systems can generally be removed without damage to allow access to the borehole.

4.0 DATA ASSESSMENT

Once the rock matrix and groundwater data have been collected and analytical results validated, the data will be evaluated. Rock matrix data will be reported on a dry mass unit basis (e.g., nanograms per kilogram - ng/kg) and porosity data will be used to estimate rock matrix pore water equilibrium concentrations and partitioning.

5.0 REPORTING

A Draft and Final Report will be prepared for USEPA review. The final report will address USEPA comments.

6.0 SCHEDULE

The coring and borehole investigations are anticipated to be completed for a single borehole within 10-12 working days. The installation of a Flute blank liner will take approximately 1-2 days. Note, Olin has obtained relevant access to install the boring at the proposed location. Olin will plan to implement the work soon after the approval of this Work Plan.

After receipt and evaluation of all groundwater and rock matrix analytical data, and validation of that data is complete, the modified FLUTe multilevel system will be designed and discussed with USEPA. Once the design is approved, the fabrication schedule will be dependent on FLUTe and their existing backlog. Once that is known USEPA will be informed of the anticipated installation date. Installation will be conducted by FLUTe systems.

The FLUTe ports will be sampled twice, approximately one month apart. Once those data are reviewed and validated Olin will prepare a Draft Report, summarizing the field activities and results. It is anticipated that report will be submitted to USEPA 45 working days after final receipt of data.

7.0 REFERENCES

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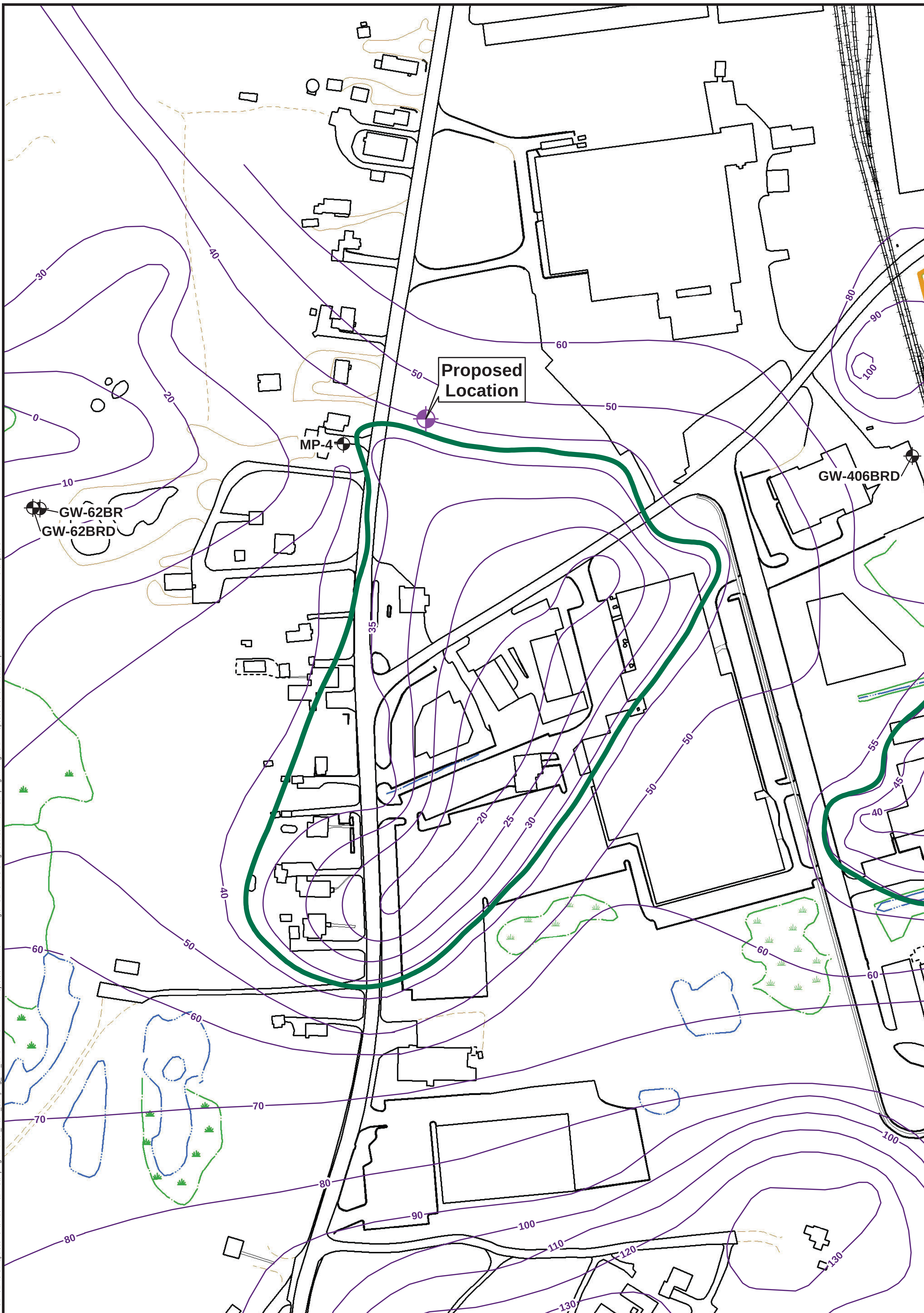
FIGURES



Legend

- Proposed Bedrock Location
- Monitoring Well
- Approximate DAPL Pool Delinelation
- 51 Eames St. Property Boundary
- Bedrock Contour Elevation (ft)
- Paved Road
- Unpaved Road
- Railroad
- Structures
- Parcel Boundary
- Surface Water
- Trails
- Wetland Boundary
- Sidewalks
- Wooded Areas

wood.

N

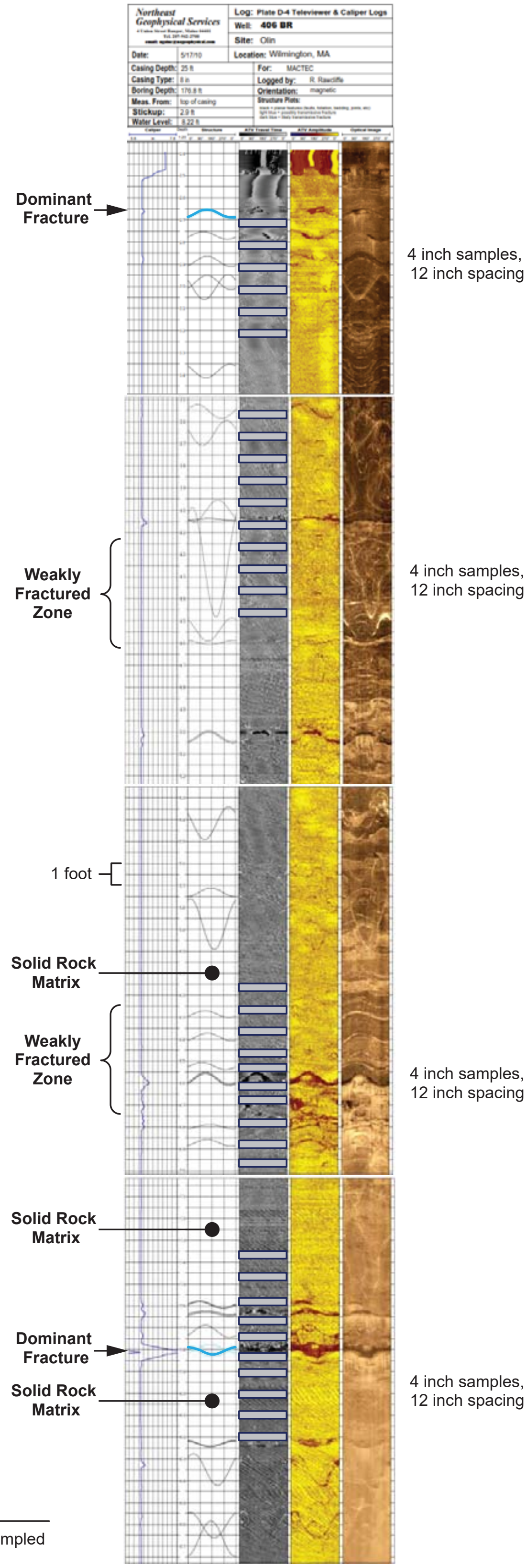
0 85 170 340 Feet

Figure 1
Proposed Bedrock Location

Rock Matrix Sampling Work Plan
Olin Chemical Superfund Site
Wilmington, Massachusetts

Prepared/Date: BRP 06/29/18 | Checked/Date: PHT 06/29/18

Document: P:\Projects\olinwlm\Olin Wilmington CERCLA\GIS\MapDocuments\Rock Matrix Sampling WP\Rock_Matrix_Sampling_WP_11x17P.mxd PDF: P:\Projects\olinwlm\Olin Wilmington CERCLA\GIS\Figures\Rock Matrix Sampling WP\Figure 1 - Proposed Bedrock Location.pdf 06/29/2018 3:00 PM brian.peters



Legend:

4 inch Core Interval to be Sampled

Notes:

1. Figure portrays a subset of rock samples to be collected depending on core recovery.
2. Sample lengths are approximate.
3. Sample spacing (approximate) to range from less than 4 to 12 inches.

Olin Chemical Superfund Site Wilmington, Massachusetts	wood.	Figure 2 Example of Rock Matrix Sample Length and Spacing Rock Matrix Sampling Work Plan

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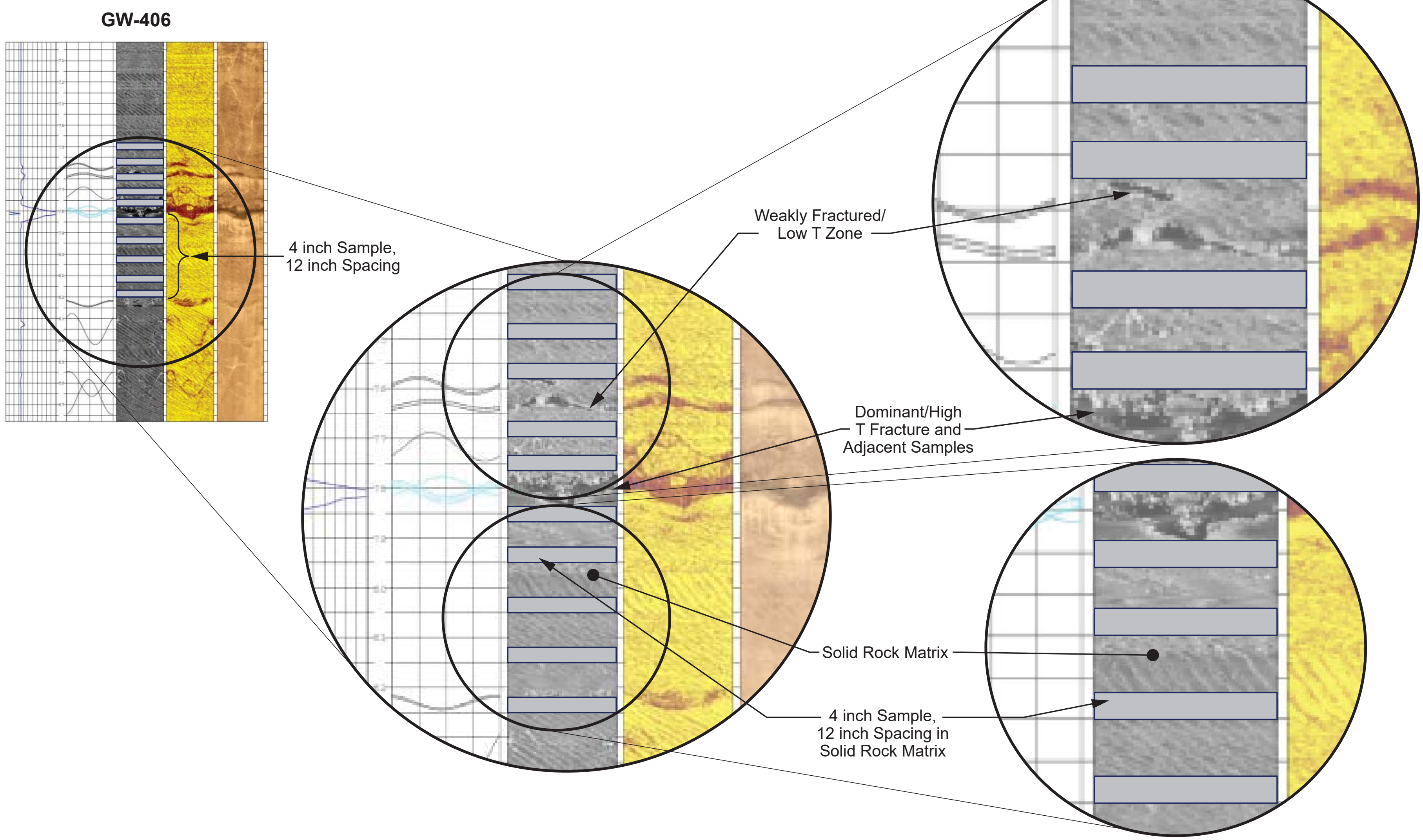

Olin Chemical Superfund Site Wilmington, Massachusetts	wood.	Figure 3 Sampling Details Rock Matrix Sampling Work Plan

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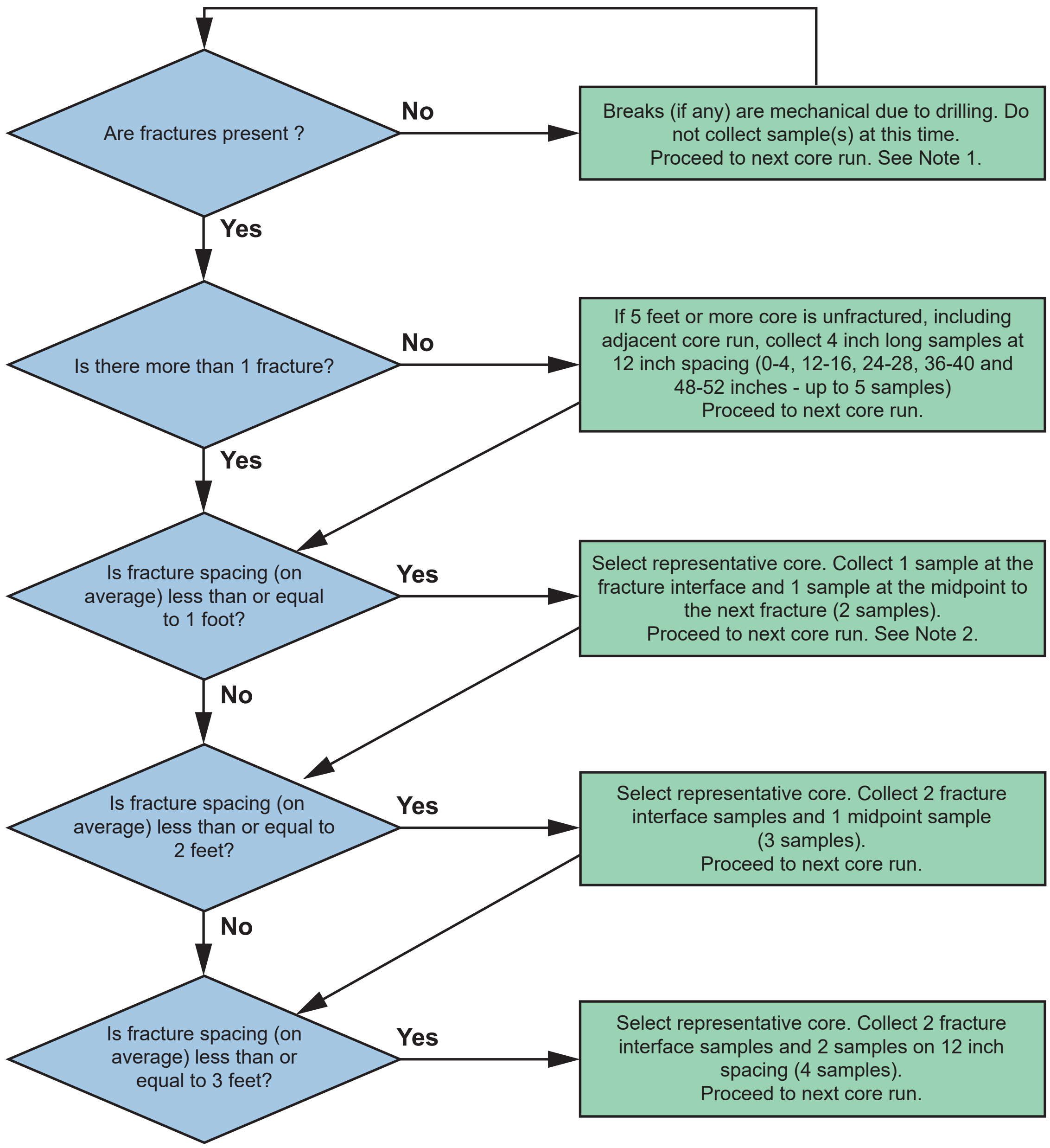


Goal of Rock Matrix Sampling:

1. Collect rock matrix samples at measured distances from identified impacted water bearing fractures for possible NDMA analyses.
2. Include samples adjacent to dominant water bearing fractures, weakly fractured zones, and from solid rock matrix.
3. To the extent possible, target rock sample lenghts of 4 inches to provide comparable results.

Directions:

For each 5 foot HX Core Run placed into the core box, use the following Decision Tree as a guide to Rock Matrix Sampling

Definitions:

Fracture = water bearing fracture (staining and/or weathering on fracture faces)

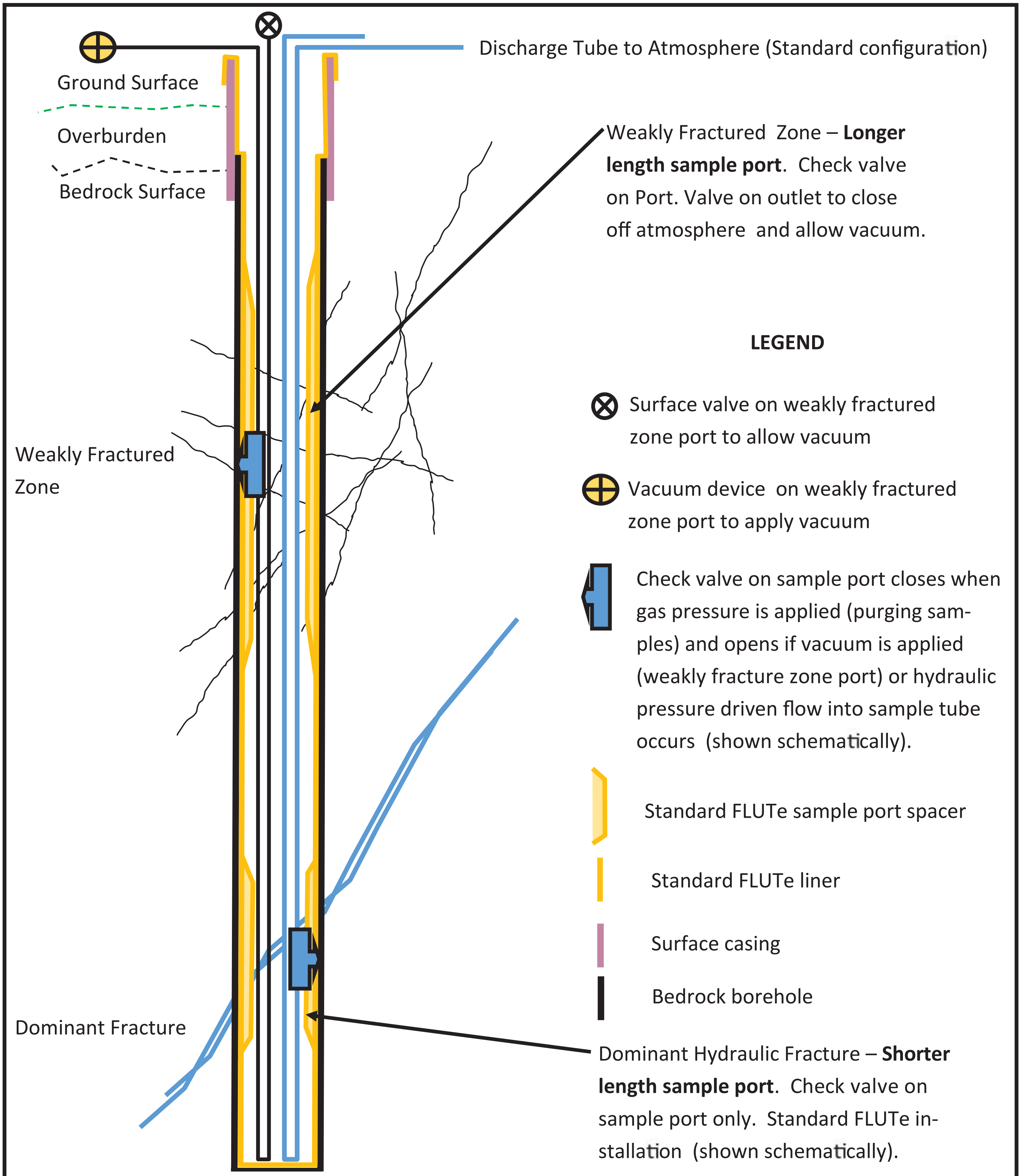
Break = a mechanical break due to drilling

Notes:

1. If no fractures are present in a core run, collect at least one sample per core run.
2. If several fractures are present in a five foot core run, select representative section of core to sample. The core does not need to be sampled on one foot intervals.
3. Sampling to be based on professional judgement, this decision matrix is only a guide.

Olin Chemical Superfund Site Wilmington, Massachusetts	wood.	Figure 4 Rock Matrix Sampling Decision Tree Rock Matrix Sampling Work Plan

PORT2018009c.ai



Olin Chemical Superfund Site Wilmington, Massachusetts	511 Congress Street Portland Maine wood.	Figure 5. FLUTe Schematic to Monitor Weakly Fractured Zone and Dominant Fracture

ATTACHMENT A

Attachment A
Response to Agency Comments Dated
May 22, 2018

Response to Comment Letter prepared by Nobis Engineering on Behalf of EPA, dated May 16, 2018:

Comment 1: *The discussion of bedrock fractures (both large scale and micro-scale) should include other boreholes in addition to GW-406. Other bedrock boreholes with long open intervals for evaluation and relatively recent borehole geophysics include GW-65BR, GW-202BR, GW-405BR and GW-407BR.*

Response:

Based on the elevated N-nitrosodimethylamine (NDMA) detections at GW-406BR and its proximity to the Main Street DAPL Pool, the borehole geophysical log for GW-406BR (and for boring SB-8 / MP-4) provide the best available site information on which to develop the Rock Matrix Sampling Work Plan. The Operable Unit (OU) 3 Remedial Investigation (RI) report provided discussion of the borehole geophysical logging of each of the requested boreholes. The intention of this work is to evaluate bedrock conditions in the immediate vicinity of the Main Street Bedrock DAPL pool, specifically on the downgradient side within the Main Street bedrock saddle. While the bedrock at these boreholes have similarities in the orientation of fracturing, each have important differences in the rock type present, the amount of groundwater impacts and degree of fracturing. Collectively these bedrock boreholes represent the range of conditions encountered across the Site and study area and they all contribute to the current site understanding and conceptual site model. However, this work plan is intended to direct the study of bedrock conditions in the vicinity and downgradient of Main Street DAPL pool.

As noted in previous RI documents the bedrock encountered in GW-202BR and the deeper portion of GW-405BR is siliceous and sparsely fractured being comprised of quartzite, which is limited in aerial extent. While GW-202BR does have elevated N-nitrosodimethylamine (NDMA) concentrations at two zones (5,800 in BRS and 1,100 ng/L in BRD), the effects of diffusion in matrix adjacent to fractures would be limited to those two very low transmissivity fractures. GW-405BR, GW-65BR, and GW-407BR are not in immediate proximity to a dense aqueous phase liquid (DAPL) pool and are characterized by low to very low NDMA concentrations in groundwater. Although diffusion is an important fate and transport mechanism even at those low concentrations, it would not be fruitful to study diffusion where concentrations in rock matrix would likely be very low.

Comment 2: *Please clarify if all the rock core samples, or only a subset of samples collected and processed for chemical analyses will also be analyzed for NDMA.*

Response:

The entire suite of rock core samples collected will be processed (e.g., crushed and extracted). Based on field observations (proximity to fractured intervals) they will be prioritized for analysis. Initially a subset of approximately 30% of the samples will be submitted for NDMA analyses with the actual number determined based on the logged rock core, including spacing and size of natural water bearing fractures. Based on the results from the first batch of submitted samples, additional samples will be submitted for analyses to refine the understanding of depth of diffusion into the rock matrix. Whether all of the samples will ultimately be analyzed will depend on results and subsequent discussions with USEPA. Note, there are no hold time restrictions for these samples prior to completion of the extraction. Once extracted the samples will be analyzed within 40 days.

Comment 3: *Please consider varying the sampling interval so that samples can be collected close to fracture surfaces as well as at varying distances from the fractures. The sampling frequency (distance between samples) may also need to vary if extensive fracture/rubble zones are encountered.*

Response:

It is certainly our intention to collect samples at varying distances from identified fractures. Pursuant to the telephone conference call on June 14, 2018, Olin developed a series of figures and a decision tree logic diagram which were transmitted to USEPA on June 26. These figures depict how a sampling strategy might be developed in the field based on observations during boring installation (and using GW-406 as a surrogate). These figures are included in the revised work plan.

The general approach will be to log all the fractures and mechanical breaks (caused by, for example, drilling) in the five-foot core and then to select and process a piece of core with an approximate length of 4 inches at varying distances from an identified fracture. Core from each five-foot run will be laid out in a core box and fit together accommodating mechanical breaks and natural fractures. Natural fractures will be identified based on surface appearance (weathering, presence of iron oxides, alteration). The recovered core length will be measured and recorded and the length of un-fractured rock cores between or adjacent to natural fractures will be estimated and recorded. Measurements to calculate Rock Quality Designation (RQDs) will be made.

Core samples will be selected to target rock matrix adjacent to and at measured distances from dominant water bearing fractures, and adjacent to and at measured distances from weak fractures within the weakly fractured bedrock. The actual samples collected will be based on professional judgement and the following general guidelines:

- If a five-foot core run is not fractured, it will be evaluated in conjunction with the adjacent cores from the prior and subsequent runs.
- If several adjacent sequential core runs are un-fractured a minimum of one sample will be collected from each five-foot core run.
- If a section of un-fractured core of a length greater that five feet in length is present adjacent to a fracture, then approximate 4-inch core samples will be collected at the following approximate distances (in inches) from the fracture interface: 0-4, 12-16, 24-30, 36-40, and 48-52.
- If there are multiple fractures within a five-foot core run, samples will be collected at the fracture margins and at specific distances between the fractures. Figure 4 of the revised work plan provides a Decision Tree for guidance on the frequency of such samples.
- If weathered rock matrix is encountered, it will also be sampled.

Comment 4: *The workplan states that FLUTe samples will be collected for an estimated four low-transmissivity zones. Will the FLUTe liner remain in place after sample collection or will the liner be removed to allow later access to the open borehole?*

Response:

Olin's intent is to collect two rounds of samples from each of the ports after installing the FLUTe system. Additional sampling needs will be evaluated based on that data. If there is a need to access the borehole, the liner can always be removed and redeployed.

Comment 5: *Groundwater samples should also be evaluated for field parameters (including specific conductivity) and for major cations and anions in addition to NDMA if sufficient sample volume is available.*

Response:

Groundwater samples will be evaluated for field parameters (specific conductivity, ORP, D.O., temperature and pH), and for major cations and anions (ammonia, chloride, magnesium, sodium and sulfate) in addition to NDMA if sufficient sample volume is available. These data will be used to aid in differentiating between diffuse groundwater and possible DAPL by estimating density using the previously developed empirical equation. The Work Plan has been revised to reflect this.

Comment 6: *The workplan includes installation of a single borehole north of the Main Street DAPL pool. Given the variations in fracture aperture between boreholes (based on a review of borehole geophysical results), evaluation of one borehole is insufficient to draw conclusions for the entire Site.*

We recommend installation of additional boreholes for evaluation downgradient of the DAPL pool: one between the two DAPL major pools (near GW-43D), one west of GW-70D, and one south or east of the GW-202 cluster. These additional boreholes may be relatively shallow (50 feet or less below top of rock) to minimize potential downward migration of contaminants. The additional boreholes would provide further characterization of bedrock in areas that have not been investigated, and would confirm bedrock fracture and matrix diffusion characteristics across the primary study area.

Response:

Based on the results of initial conceptual modeling presented during several previous meetings including those on February 7 and 8, 2018, USEPA stated that if the model results are correct, then we should be able to drill a bedrock hole near the Main Street DAPL pool and NDMA should be present in the rock matrix at that location. Olin agreed that this was a data gap and indicated that we would drill a borehole as suggested to verify the conceptual model. Therefore, our objective for this work has been (and continues to be) demonstration that the model presented to USEPA is technically verifiable. To accomplish this, Olin is proposing to focus efforts on drilling the proposed location on the down gradient side of the Main Street DAPL pool where the potential for measuring matrix diffusion is greatest. We anticipate a single borehole, as proposed, will provide a range of fracture conditions as well as NDMA concentrations, which decrease with depth. Since diffusion is dependent on concentration and time, this assessment will provide data to interpret the potential extent of matrix impacts. Given the location of the Main Street DAPL pool, it is not feasible to continuously drill step-out bedrock boreholes, nor is it necessary or appropriate. Also, the work Olin has completed within and adjacent to the Containment Area clearly demonstrates that the bedrock beneath the containment area is competent to depths greater than 100 feet from the top of rock elevation. As such, the DAPL within the containment area is not mobile and drilling an additional bedrock borehole (or boreholes) in the vicinity of GW-202BR will not provide information that is useful in determining an appropriate remedy for this site. Furthermore, based on existing USGS regional bedrock mapping, it appears evident that the bedrock in the vicinity of well GW-202BR is a different type of rock (quartzite) than what would be anticipated downgradient of the Main Street DAPL pool. The two rock types most likely have different physical characteristics such that a linear interpretation of data from the area around well GW-202BR in comparison to that in the area of the Main Street DAPL pool is likely inappropriate.

Response to Memorandum Prepared by William Brandon, EPA Hydrologist, May 10, 2018:

Response to General Comments:

Comment 1. ***Issues regarding location(s) to be cored and tested*:** During the meeting of December 13, 2017, in response of OLIN's expressed intentions to assess matrix diffusion/back-diffusion potential at the site, EPA summarized several recommendations designed to produce a technically defensible result. The comment is repeated here:

To make a compelling case regarding the importance of bedrock back-diffusion with respect to groundwater contamination, the following information will need to be more accurately resolved:

- *The location of the centroid of maximum DAPL concentration with respect to the vertical dimension in relation to the top-of-bedrock surface and other features of interest (see previous issues and recommendations)*
- *The location of existing control points with respect to mapped or interpreted fractures at the site scale.*
- *The location of sample point with respect to mapped fractures at the borehole scale.*
- *Vertical resolution/uncertainty of sampling with respect to resolution/uncertainty of DAPL mass centroid, fracture locations, etc.*
- *A more highly discretized sampling strategy, particularly in the vertical dimension should be considered for the future.*

It was also stated that, "The robustness of a conclusion that a particular sample has been collected from an un-fractured area is key to this assessment. If it cannot be demonstrated that a particular sample has been collected from an un-fractured region (i.e., from the rock matrix), then the strength and robustness of any back-diffusion assessment is diminished considerably."

*In consideration of these points, it is not clear how the **location** identified in the [Draft] Rock Matrix Sampling Work Plan was selected? What are the **technical reasons** which make this location favorable for detailed assessment of matrix diffusion/back diffusion? It is noted that the location selected is approximately 30 feet north of the mapped northern boundary of the Main Street DAPL plume. However, what is the **resolution** on this map boundary? (i.e., horizontal resolution/uncertainty). In addition to the issue of horizontal resolution/uncertainty, the **other issues** listed above must be quantified. It is simply <u>essential</u> that the position of the location(s) to be tested are well-defined in 3-D in relation to delineated contaminants within the overburden and bedrock units.*

<u>Response:</u>

The following responses are organized according to the major topics in Mr. Brandon's comment that we have bolded in the above paragraph.

Location Selection. The preliminary conceptual 2-D modeling to simulate fate and transport of NDMA in fractured bedrock was based on data associated with the Main Street DAPL pool. Additionally, Olin's contention continues to be that removal of the Main Street DAPL pool is unnecessary and inappropriate because back diffusion of NDMA from the local bedrock matrix will prevent ARARs from being met in any reasonable time frame. The model results indicated both matrix diffusion and matrix advection (advective transport through low hydraulic conductivity bedrock) would cause recalcitrant, long term impacts to bedrock groundwater. USEPA stated, during meetings held on February 7 and 8, 2018, that if such predictions were true, Olin should be able to verify those predictions by installing a boring at a location in the vicinity of the Main Street DAPL pool and find NDMA in the rock matrix at that location.

Olin therefore selected a location in proximity to the Main Street DAPL pool. The location was based on existing data from the Main Street Bedrock Saddle Investigation and in particular boring SB-8 that was completed as multi-level piezometer MP-4. The proposed location was selected as near as possible (approximately 160 feet) to existing multi-level piezometer MP-4 without infringing on private residential property. The MP-4 location is well characterized and the data indicate bedrock on the down gradient side of the Main Street DAPL Pool is located down dip along fractures that are oriented toward and under the western side of the Main Street DAPL pool. The proposed location, similar to MP-4, is on the downgradient side of the DAPL pool and in a down dip direction of fractures oriented toward and under the DAPL pool. Details of the characterization effort that defined the Main Street Bedrock Saddle are contained in Geomega Technical Report Series XVII (Geomega, 2001) which was discussed and provided to USEPA previously (MACTEC, 2009; Amec Foster Wheeler, 2017). These references are included in the work plan references.

MP-4 underwent an extensive characterization consisting of hydraulic packer tests, borehole geophysical logging, and hydrophysical logging performed in the bedrock portion of the boring to determine fracture density and orientation and the hydraulic conductivity of transmissive fracture zones. These tests were also performed in open sections of monitoring wells GW-62BR and GW-62BRD to establish comparative data for adjacent areas in the Western Bedrock Valley. MP-4 encountered diffuse groundwater in fractures to a depth of approximately 175 feet bgs (110 feet below top of rock) where the boring was terminated. Two ports contained DAPL based upon specific conductivity values. It is Olin's opinion that the greatest likelihood of impacts from both matrix diffusion and low K bedrock advective transport would be in this portion of the Site. In lieu of installing a boring through the DAPL pool, Olin believes it more prudent to install a boring on the immediate down dip side, and has proposed the location accordingly. Figure 1 of the revised Work Plan shows the approximate locations of the proposed boring and MP-4, GW-62BR, and GW-62BRD.

Technical Reasons. The rock matrix sampling is intended to document NDMA contaminant mass in rock porosity adjacent to fractures that have been in prolonged contact with either DAPL or diffuse groundwater. Volumetrically, the largest source of NDMA is the Main Street DAPL pool. NDMA has a published diffusion coefficient of 0.84 cm^2d^{-1}, (GSI Chemical Data Base. https://www.gsi-net.com/en/publications/gsi-chemical-database/single/404-nitrosodimethylamine-n.html), which yields a migration distance of approximately 6 feet by diffusion processes alone in 3-dimensional space over a 60-year period (the approximate time the DAPL pool has been present) based on Fick's Law. The transport of NDMA by advection was also considered by the numerical modeling, and depending on effective hydraulic conductivity

(K), migration of NDMA by advection may be greater than by diffusion alone. To verify NDMA transport by diffusion, areas of the Site where highest NDMA concentrations are present would be ideal, and in this case, in the vicinity of the Main Street DAPL pool. We also wanted to ensure that the testing location would provide a range of concentrations of NDMA in groundwater to allow a better understanding, to the extent feasible, of what affect varying groundwater concentrations may have on matrix impacts. Since concentrations of NDMA decrease with depth in bedrock (as observed in MP-4 and in other locations at the Site), testing over a range of concentrations can be accomplished via a vertical borehole in bedrock at a single location by the Main Street DAPL pool.

The total mass that can be stored in the bedrock matrix is a function of porosity and dissolved concentration. Bedrock porosity, in general, varies over large ranges depending on rock type and/or degree of weathering. Matrix diffusion is equally applicable to low K unconsolidated porous media such as clays and silts (Parker et. al 1994, Parker et al 1997). In a like manner, matrix diffusion is also a process that occurs in weathered bedrock, in particular where porosity has been enhanced by weathering processes. Matrix diffusion is not applicable solely to un-fractured and un-weathered bedrock. It is important to test the geologic conditions that exist at the Site that are within and typical of the main area of impacted groundwater since the objective ultimately is to evaluate whether achieving ARAR's is technically feasible.

Resolution The resolution or certainty of the northwestern side of the Main Street DAPL pool is well defined by numerous soil borings and seismic lines conducted for the Main Street Saddle bedrock investigation.

Other Issues

<u>First Bullet</u>. The meaning of this bullet is unclear. DAPL is a dense liquid and does not have a concentration although specific conductivity and density can be used as a measure of how concentrated DAPL may be at any given location. The Main Street DAPL Pool is the center of NDMA mass and concentrations of NDMA as well as other dissolved constituents increase progressively with depth within the DAPL pool. The highest concentrations of dissolved constituents typically occur along the bottom of the DAPL pool and then diminish progressively with depth (measured over 100s of feet) in the underlying bedrock. Furthermore, we do not believe a refined understanding or estimation of the centroid of NDMA mass within the bedrock matrix is necessary to accomplish the objective of model verification as discussed above. The purpose of the numerical model is to simulate expected behavior of the contaminants over long periods of time considering contaminant mass associated with advective and diffuse transport in the bedrock and observed dissolved phase contamination in groundwater.

<u>Second Bullet.</u> The intent or meaning of this bullet as written is also unclear. All investigation locations are surveyed to an accuracy of 0.01 feet. Seismic lines were typically located by GPS with sub-meter accuracy. Therefore, borehole geophysical logs can be accurately represented in

three dimensions. Fractures at the borehole scale are not projected or interpreted to extend at Site scale. The only Site-scale features that are interpreted are the sequence of faults within the Western Bedrock Valley and the Bloody Bluff Fault. Those features are located based on surveyed locations of the seismic lines. The location of the latter is based on the interpreted location of the fault from published geologic maps. Other than national geodetic monuments, (https://www.ngs.noaa.gov/NGSDataExplorer/) there are no other permanently established survey control points.

Third Bullet. In the phrase "location of sample point", the type of sample is not defined and we are unclear what sample point this bullet refers. Rock matrix samples will be located with respect to fractures at the borehole scale as described in the Response to Nobis Comment 3.

Fourth Bullet. Sampling core in boreholes is subject to vertical uncertainty when core recovery is low. The sample location can still be described by physical measurement of distance from fractures logged in the core, which in some cases can be correlated to borehole digital logging images. From the results obtained at MP-4, only two sample ports initially showed indications of DAPL based on specific conductance; Port No. 9 at the bedrock interface (22,500 µS/cm) and Port No. 5 (26,900 µS/cm) approximately 45 feet below the bedrock surface. All other ports in MP-4 contained diffuse groundwater.

The final paragraph below the last bullet speaks to the need to sample un-fractured bedrock with a negative consequence of not doing so of diminishing the strength and robustness of any assessment of back diffusion. Samples collected will be documented by their distance from identified fractures. We anticipate the borehole may encounter a wide range of conditions including larger sections of un-fractured rock that can be sampled at appropriately discretized intervals to assess the mass distribution in rock by diffusion only. Where fractures are more frequent, sampling will be conducted regardless since the objective is to characterize the actual site conditions that exist. The assessment of back diffusion will be based on numerical simulations that will incorporate the findings of this work.

As core is processed, an effort will be made to sample core at progressively farther distances from a known fracture or fractures, however depending on the nature of fracturing, some samples of rock matrix may be surrounded by weakly fractured bedrock and it may not be possible to be far removed from a potential low K water bearing fracture. In some instances (based on professional judgement) core may be sub-sectioned for sample processing and may only consist of several inches of core as the length of the core with un-fractured rock matrix can only be determined in the field during drilling. Healed fractures will be assumed not to be water bearing by definition. Water bearing fractures should be represented by natural breaks in the core, perhaps in some cases with evidence of oxidation. Iron sulfides were sparse where rock had been cored by sonic methods under OU3, and it was not common to see iron oxides on fracture faces, though some alteration of feldspars was occasionally apparent.

If diorite/gabbro is intercepted in the borehole, there may be some runs of core that are massive in texture and quite competent (based on rock quality designation (RQD) measurements and criteria). These cores will simply be processed at one-foot intervals without further sub-sectioning. In all cases, an accurate description of the sample interval selected and its relationship to the core run will be documented including photo documentation.

General Comment 2:

The matrix diffusion assessment must include known areas of high-concentration dissolved-phase or DAPL contamination contained in identifiable zones in bedrock fractures or in overburden units in contact with bedrock) and areas of unfractured matrix at successive distances from these loci of known high-concentrations of contaminants. In this respect, EPA's assessment concludes that it is likely that more than one location will need to be cored and tested. For example, for the proposed location, it is not known if the bedrock/overburden contact at that location is highly contaminated or not. Moreover, the fractures to be identified at that location are not known, nor will it be clear (without further testing) whether any fractures encountered are interconnected with fractures in contact with DAPL and/or highly contaminated dissolved-phase contaminants, such as one might expect at locations beneath the mapped Main Street DAPL pool. Additional efforts are needed to support locations for testing.

Response:

The location proposed in the draft Work Plan for the matrix diffusion assessment was based on the following factors:

- Proximity to the Main Street DAPL Pool and Main Street Saddle where high concentrations of NDMA have been documented in MP-4. Port 10 of the MP-4, just above the bedrock surface, detected 11,000 ng/L NDMA which diminished to 5,700 ng/L in Port 2 (90 feet below the bedrock surface)
- NDMA results for nearby downgradient monitoring wells in bedrock ranged from 16,000 to 13,000 ng/L at GW-62BR and 8,100 to 2,200 ng/L at GW-62BRD. NDMA at adjacent deep overburden was detected from 24,000 to 4,500 ng/L at GW-62D (see Figures 1.4.3, 1.4-5 from the OU3 RI), and
- Access

We anticipate the bedrock conditions encountered at the proposed location will be similar to known conditions at MP-4. The number and frequency of fractures in almost every borehole are unique to that specific borehole. The geology and nature of fracturing at GW-406BR on the opposite side of the Main Street DAPL pool are generally consistent with observations at MP-4. Based on the results of MP-4 and GW-65D/BR, we also anticipate the bedrock/ overburden interface will be impacted by diffuse groundwater and highly contaminated. All this data was presented in the OU3 RI as well as discussed in meetings to ensure that USEPA was made aware that the down gradient side of the Main Street Bedrock Saddle meets all the criteria suggested by USEPA. Additional efforts are not required to support locations for testing.

As described in the Work Plan, four separate data collection methods (bedrock core logging, borehole geophysical logging, packer sampling, FLUTe transmissivity profiling) will be deployed to identify both high and low transmissive zones in the bedrock, as well as zones of unfractured rock matrix. Results from these field efforts will provide multiple lines of evidence for identifying impacted transmissive fracture zones, and solid rock mass from which to select rock samples (collected, processed and preserved during drilling) for laboratory analyses.

General Comment 3: Study Design-Minimum number of testing locations: *As the problem is minimally a three- dimensional one, and a single boring only explores the Z-dimension at that location, it stands to reason that a minimum of three borings will be needed for coring and associated testing. The greater the complexity of the fracture system, the greater the number of borings that will be needed to assess it. The following represent some of the basic scenarios to consider in designing a test:*

a. In its simplest case, matrix diffusion could be assessed by evaluating the distance and degree of penetration into the unfractured bedrock matrix, assuming one can identify a location where this condition exists. As an example, OLIN has asserted that the bedrock under the containment cell is unfractured and tight and essentially provides in effect a natural but effective bedrock "liner" for the contaminants above, which inhibits their downward migration. Designing a test involving one or more bedrock boreholes drilled directly through the waste cell and into the "tight" bedrock below would provide an opportunity to validate OLIN's assertions, and if validated, unfractured bedrock matrix immediately below the critical interface (presumed to be at the bedrock/overburden interface), could be assessed with respect to matrix diffusion potential at successive distances from the interface.
b. Another option is to identify a known fracture containing highly contaminated groundwater and/or DAPL, and to design a test to assess matrix conditions at successive distances (into unfractured matrix) from the impacted fracture. This would involve first identifying such a condition, either in a new or existing borehole, and planning additional borings to intersect the unfractured matrix surrounding the fracture at successive distances away from the feature.
c. A third option involves a more complex, and perhaps more likely scenario where contaminated fractures as well as the boundaries/limits of the DAPL pool are critical locations where matrix diffusion/back diffusion is assessed and compared to measurements at successive distances away from these and points of reference in matrix domains which can be demonstrated to be unfractured.

The study design must incorporate this degree of resolution. It seems unavoidable that at least several borings will be required. Please revise the study design and resubmit for review.

<u>Response:</u>

The proposed testing is intended to answer two fundamental questions. Can the conditions of 1) matrix diffusion and 2) (low K) matrix advection simulated by conceptual numerical modeling be demonstrated physically in the field. This requires only a single boring to be installed in a known highly contaminated bedrock and that it be considered representative of other less accessible portions of the Site, in particular, within the Ipswich watershed. If matrix impacts can be demonstrated at the proposed location, then it can be presumed with a higher degree of certainty the same processes will control contaminant fate under similar geologic conditions at comparable dissolved NDMA concentrations. It is anticipated that with increasing depth, the NDMA concentrations will decrease and vertical sampling will allow an assessment of these processes at lower dissolved concentration of NDMA. Thus one boring will allow evaluation of matrix impacts from high to low concentrations.

Another significant problem related to technical practicality of implementing remedy is heterogeneity of aquifer properties (fracture transmissivity) and chemical distribution (potential higher concentration in lower K zones). A good example of this issue was demonstrated at the Eastland Woolen Mill Site. The fracture network, there, like Wilmington and many other sites, contains numerous low transmissivity fractures (mostly bedding plane) that are cross connected by a small subset of dominant high(er) K fractures. Due to this heterogeneity, when the system is pumped for an extended time, the higher K fractures (only a smaller % of known fractures) dominate and act as the primary boundary conditions governing the aquifer response to pumping. Since the lower K fracture network and associated rock matrix are also impacted, groundwater extraction is ineffective as a mass removal strategy. Additional graphics supporting this argument can be provided if needed.

General Comment 4: Study Design – Solid Phase Sampling discretization, Core (DFN):

It is stated in the work plan that core will be processed at one-foot intervals following the Core DFN approach. This indicates that the minimum resolution of this method will be 1-foot, or greater. In practical terms, a core sample which intersects a fracture will be unable to discern between contamination within the fracture and that within the adjacent matrix as both end members are comingled in the crushing, sample preparation and analytical process. Under such a scenario, even if contaminants were detected in the core subsection adjacent to one intersecting a fracture, (assumed to be in unfractured matrix), depending on the vertical position of the fracture, there will be a large error bar on the sample location with respect to distance from the known fracture. At worst, a 1-ft interval immediately adjacent to an interval with a fracture may "take credit" for contamination throughout the 1-foot interval, when it is not known whether the contamination is distributed evenly within the 1-foot matrix section or just within a thin zone at one end of the core. Since the depth of penetration into matrix is a critical factor in estimating back-diffusion cleanup time, it is not clear that the level of resolution called for in the present study design is sufficient to answer the critical questions. A finer degree of resolution is called for. More importantly, additional *clarification is needed as to what means will be employed to discriminate between contamination ascribed to 'unfractured' matrix vs. that ascribed to large fractures vs. lightly fractured matrix containing secondary fractures which may be connected to larger fractures in non-obvious ways, e.g., via connections which may not be wholly discernable from the perspective of a single borehole. As an example, a fracture not penetrated by a borehole may connect with a second fracture, also not penetrated by a borehole, which intersects a third minor fracture which is intersected by the borehole. Under this scenario, contamination from this interval may be inappropriately credited to 'matrix'. Additional steps are needed to ensure that "matrix" bound contamination is properly accounted for and is not biased high by "false positives" from unaccounted- for-contributions from minor (secondary) fractures. Again, the process for identification and "validation" of unfractured matrix is a necessary prerequisite to a proper application of the Core DFN approach to assess matrix diffusion penetration distances.*

Response:

Rock matrix affected by "Secondary" fractures is relevant to this investigation. Contamination detected in matrix at such locations are not false positives and the sampling will account for location with respect to all identifiable fractures. Sampling rock that contains a fracture does not mean the fracture biases the sample, it simply means the sample consists of rock in immediate proximity to a fracture.

Please see response to General Comment 1 and response to Nobis Comments for additional detail and discussion of the sampling strategy.

General Comment 5: Use of FLUTe System

Response:

Comment acknowledged. Olin will engage USEPA in additional discussions as warranted.

General Comment 6: Role of matrix diffusion modelling. *On February 7, 2018, Dr. Neven Kresic presented results of preliminary "conceptual" matrix diffusion/back-diffusion modeling simulations at the site based on various assumptions. These simulations seemed to suggest that contaminants could penetrate the matrix to distances on the order of 100 feet from a highly contaminated fracture on time scales consistent with the site history. This seems unlikely, at best, and the actual values for penetration distances may be much lower. It is essential that any matrix diffusion field tests are deliberately designed to test/constrain the modeled matrix diffusion penetration distances with known values. Unfractured matrix should be measured at discrete intervals at progressive and measurable distances from impacted fractures. If the 1-foot discretization selected is too coarse, a finer-scale approach may be needed (i.e., discretization < 1-ft). The modeling work should be consulted to determine which other assumptions in the modeling might benefit from constraints from collection of site-specific data.*

<u>Response:</u>

The modeling was conducted to simulate both matrix diffusion and advection with dispersion. As discussed previously, diffusion in and of itself as modeled has a limited transport distance from the fracture interface, but is an essential element in considering fate and transport of organic contaminant in fractured – fractured /porous media. This is consistent with the findings of the modeling as presented in Appendix H of the Draft OU3 RI Report (Amec Foster Wheeler, 2018). Diffusion is important both for attenuation of plume fronts as well as significantly lengthening the time frame for remediation.

With regard to sample discretization, please see response to General Comment 1.

<u>Response to Specific Comments:</u>

Specific Comment 1: Section 2.1, Background Discrete Fracture Networks (DFN) Approach*; The text states that, The DFN approach focuses on detailed characterization of borehole hydraulics and groundwater and rock matrix contaminant distribution," yet the only citation provided for the method (Parker, 2007) is a conference presentation. Please provide references to peer-reviewed journal articles which describe the method in appropriate detail.*

<u>Response:</u>

The CORE DFN approach is not a new technology – it is a synthesis of established investigation and data assessment technologies that have been in existence for many years into a unified system or methodology specific to discretely fractured bedrock. The DFN approach arose from a number of research projects and published articles by individuals who worked in collaboration with University of Waterloo and Guelph University since the mid-1990s. These include primarily Dr. Beth Parker, Dr. John Cherry, Steve Chapman, Carl Keller and numerous other individuals. A listing of publications by Dr. Parker is available through several sources including:
http://www.soe.uoguelph.ca/webfiles/bparker/pages/Publications.html,
https://scholar.google.com/citations?user=5HdorQUAAAAJ&hl=en.

To our knowledge no singular peer reviewed paper describing the DFN approach was ever published. The CORE DFN developers and authors appear to have chosen to present the approach and concepts at the USEPA sponsored National Groundwater Association fractured bedrock conference series as well as other conferences. A more recent published version of the DFN approach may be found on
https://g360group.org/home/highlights/publications/other-publications/ and is attached.

The peer reviewed articles, which formed the basis of the DFN approach are too numerous to list here and included papers on depth discrete multilevel monitoring in fractured bedrock, rock core sampling, EPM (equivalent porous media) and fracture flow modeling of contaminant behavior, cross contamination in open boreholes, detailed hydrostratigraphic characterization, plume persistence due to back diffusion, microwave assisted extraction techniques, diffuse loss of DNAPLs in fractured porous media and related topics.

The DFN approach in essence is similar to and expands upon methods we developed and/or used in fractured bedrock characterization at Loring AFB in the 1990s (rock matrix sampling, EPM and fracture flow modeling, borehole geophysical logging, discrete zone packer sampling) and later at Eastland Woolen Mill (rock matrix sampling, EPM modeling, borehole geophysical logging, inter-well HPFM testing, discrete zone packer sampling, FLUTe systems, borehole electrical resistivity tomography, and partitioning inter-well tracer testing).

The purpose of the citation was educational for those stakeholders in particular who might not be familiar with discrete fracture network characterization methodologies. The approach as described by Dr. Parker consolidates and does an excellent job explaining an integrated and systematic investigation methodology and technology options that are considered to be the current state of the practice in the science.

Specific Comment 2: Section 2.2 Problem Statement, Page 4, P 2*; The text states, "From a conceptual standpoint the fractured rock -matrix system typically includes a dominant set of fractures with several different orientations that cross connect and provide hydraulic continuity across the bedrock system. This allows groundwater to move in response to hydraulic head but the predominant movement is controlled by connected fractures as well as fracture orientations. Over a representative volume of the aquifer, these systems are generally conceptualized and evaluated to behave approximately like porous media. The intervening blocks of bedrock defined by the intersection of these major fracture sets are not monolithic and are commonly weakly fractured. The weakly fractured bedrock and the hydraulically dominant fractures are connected and are both in intimate contact not only with the groundwater contained within fractures but also with the adjacent rock matrix." This conceptual statement outlines the system as essentially having 3 major components, as follows:*

1. *Dominant hydraulically-significant cross-connecting fractures;*
2. *Weakly fractured rock adjacent to and between dominant fractures;*
3. *And the adjacent rock matrix (unfractured).*

Since the theory of matrix diffusion pertains to the unfractured rock matrix, it stands to reason that any effort to quantify matrix diffusion at particular locations rests on the ability to identify technically defensible volumes of unfractured rock matrix at measurable distances from impacted strongly- and weakly-fractured rock. The statement that, "The intervening blocks of bedrock defined by the intersection of these major fracture sets are not monolithic and are commonly weakly fractured. The weakly fractured bedrock and the hydraulically dominant fractures are connected and are both in intimate contact not only with the groundwater contained within fractures but also with the adjacent rock matrix," is somewhat misleading. While it is generally true, this implies that there it is acceptable to assess matrix diffusion in the "intervening blocks" between dominant *fractures, even if these blocks contain "weakly fractured rock". EPA rejects this notion, and to clarify, we will insist that "matrix diffusion" is assessed only in portions of the rock mass which are demonstrably unfractured with either minor or major fractures, yet can be related by measurable distances to specific fractures or zones of smaller scale fracturing.*

Response:

We believe USEPA has misinterpreted our statement – Olin's intent is to sample both fractured and unfractured portion of the bedrock to be encountered in the proposed location. The theory of matrix diffusion pertains to rock matrix that is located between fractures as well as away from fractures. If the distance between fractures is greater than diffusive transport, there should be regions of rock where matrix is not impacted. The hydraulically dominant fractures (using GW-406 BR as an example) are typically intersected 50 to 75 feet apart. Un-fractured rock matrix is present adjacent to these fractures. Smaller discrete fractures are also present and prevalent between the large fractures but by definition have much lower transmissivity. These occur and intersect at a much higher frequency, have very small apertures but we believe them to be equally contaminated and also have un-fractured rock matrix adjacent to them. As discussed previously, hydraulically active fractures, even those with very low transmissivity have aperture that will cause natural breaks in the rock core.

We believe sampling should encompass all conditions encountered in the core which have potential to retard migration of contaminants in bedrock. To suggest only large volumes of un-fractured rock are pertinent to matrix diffusion could bias the evaluation. We believe all conditions in the rock mass should be quantitatively evaluated.

Specific Comment 3: Section 2.2 Problem Statement, Page 4, P 3*; The text states, "Matrix diffusion is one of the primary physical processes that transfers dissolved constituents from secondary porosity features (such as faults and fractures) into the adjacent primary rock matrix porosity by chemical diffusion. Diffusion is usually described by Fick's first law relating the chemical's diffusion coefficient to distance and time." The text further states, "Hence, to understand and estimate groundwater remedy duration, it is critical to estimate and/or quantify the contamination in rock matrix." As noted in the comments above, the calculated matrix diffusion will vary with distance from a particular fracture or region fracturing. As such, the key parameters are as follows:*

- *Time (t)*
- *Distance (into primary rock matrix at time (t))*
- *Contamination (total mass contained in rock matrix at time (t))*

As stated in previous comments, the ability to apply this theory in the fractured rock setting depends on ability to accurately and precisely identify the contact between primary porosity (unfractured matrix) and secondary porosity (defined by fractures, both major and minor), and the ability to accurate measure mass in rock matrix at progressive distances from the contact between primary

(ϕ1) and secondary porosity (ϕ2). The degree of resolution is therefore the sum of the accuracy and precision of each of the measurements, as follows:
Matrix Diffusion Resolution =

- *Measurement accuracy/precision on delineation of (ϕ1)/ (ϕ2) boundary +*
- *Measurement Interval in rock matrix at progressive distances from (ϕ1)/ (ϕ2) boundary (1-foot) +*
- *Measurement accuracy/error in measuring core at 1-ft increments (accounting for hole drift, core loss and unrecovered core intervals and sub-sections, measurement accuracy relative to fixed reference point, etc.)*
- *= >> 1-foot*

Since the measurement increment for subsampling of core is given as 1-foot, the actual total error on an estimated distance of a specific measurement from the boundary between primary (matrix) and secondary rock (fractured) may be much greater than 1-foot. The accuracy and precision of the actual delineation of the boundary between primary/secondary rock porosity is therefore highly dependent on the ability to identify and delineate the boundary between primary/secondary rock porosity in 3-D both laterally and vertically from a fixed point of reference. The work plan needs to include additional details as to how this will be accomplished.

Response:

As discussed on the phone conference call June 14, and in response to Nobis Comment 3 above, Olin has clarified its approach to sample selection and additional detail is provided in the revised work plan. After a given core run is logged and both mechanical breaks and natural fractures are identified, discrete samples of core will be collected at progressively larger distances from identified fractures. Therefore the distance from the fracture surface to the sample will be known. Granted core recovery will cause some uncertainty in these measurements, the core recovery from the nearest location SB-8/MP-4 was good (>85%). RQD averaged approximately 50% (indicating 50% of the core was greater than 4 inches in length) at MP-4 location. With these parameters, we should be able to estimate the accuracy in assigning the core sample in its position relative to the nearest water bearing fracture.

After drilling, core logs and photos will be compared with borehole geophysical logs to resolve to the extent possible uncertainty with correlation of fractured intervals.

Specific Comment 4: Section 2.2 Problem Statement, Page 4, P 4*; The text states that [typical approaches], "do not consider the potential long-term importance of intervening weakly fractured bedrock as a contaminant storage reservoir that is part of the fabric of the bedrock matrix structure." This statement is false and misleading. As stated previously, the bedrock is conceptualized as unfractured matrix (Primary porosity) and fractured bedrock (secondary porosity). The secondary porosity includes both primary hydraulically-significant fractures as well as smaller scale features adjacent and connected to the primary fractures. As the text also notes,* *"These zones of weakly fractured bedrock not only intersect the boreholes where studied but also the fracture planes where the bulk of groundwater is transmitted." This statement therefore contradicts the previous assertion, as zones of weakly fractured bedrock which intersect hydraulically-significant fractures cannot be conceptualized both as "part of the fabric of the bedrock matrix structure" if they are also part of the interconnected network of minor and major fractures. This flawed logic must be corrected and the study needs to be redesigned accordingly.*

Response:

We believe USEPA is misunderstanding our statements. The referenced statement is certainly true. Our intent is to convey that bedrock matrix is adjacent to both large transmissive fractures and also the small fractures within the "weakly fractured bedrock". The rock that exists between these fractures can, and we believe does, contain NDMA in the primary porosity following diffusive mass transport after being in contact with impacted groundwater for decades. This clear scientific concept has been demonstrated many, many times and is unassailable. The weakly fractured bedrock is still connected to the larger fracture network, though the transmissivity of these small fractures would be less than the larger fractures. The fact remains that at most sites, the importance and role of the weakly fractured bedrock on contaminant transport is not well understood because wells are typically screened across the most transmissive fractures and not the intervening zones of bedrock with low yield. We have termed this the "fabric of the bedrock matrix structure" for lack of better words or defined terminology in literature. We can come up a different term to describe this concept if necessary.

Specific Comment 5: Section 2.2 Problem Statement, Page 4, P 5; *The text describes 4 primary hydraulically significant fractures identified in GW-406, and goes on to state, "These four fractures clearly dominate the hydraulics of the borehole based on HPFM data; however, inspection of the caliper, ATV and optical logs reveals that more than 30 additional fractures are present, many very fine in character, others more conspicuous. All these additional fractures in addition to the four main transmissive fractures would be an integral part of the chemical mass storage behavior of this bedrock." EPA concurs with this statement to the degree that the secondary fractures are connected to the primary hydraulically- significant fractures. If this is the case, then, the vertical extent of the fracturing penetrated by this borehole may indeed represent a significant aggregate reservoir of porosity able to store contaminants. However, this can no longer be realistically determined/discriminated at the existing GW-406 borehole due to the presence of the open borehole, which has cross connected fractures which may or may not have been connected in the absence of the borehole. As such, any "matrix diffusion" determined from particular fractures may include borehole effects and thus may overestimate the actual values. These issues notwithstanding, the high degree of fracturing alone at GW-406 does not make it a good candidate for further matrix diffusion testing. Rather than selecting a location such as that encountered at GW-406, it would be far preferable to choose an area with more discrete fracture zones separated by larger intervals of relatively unfractured rock matrix. GW-405BR and GW-202BRD for example, penetrated an upper interval of fractured rock underlain by a relatively thick zone of relatively unfractured rock, with a second fractured interval at depth, in turn underlain by a second, thick* *zone of relatively unfractured rock. These locations represent more straightforward conditions around which a less equivocal series of matrix diffusion testing can be designed. It is not clear why the conditions exhibited at GW-405BR are thought to be favorable for testing? Nor is it clear why the proposed location near the Main Street DAPL pool is believed to present favorable characteristics relative to designing appropriate tests to determine matrix diffusion estimates? EPA believes considerable addition effort is needed to produce an acceptable test design. EPA is prepared to convene a technical meeting to reach a consensus on the basic elements of such a design and most favorable locations at site to conduct this testing*

Response:

The concept of whether matrix diffusion occurs is not at issue; that has been established in literature and the proposed work is not intended to "unequivocally" study the process of matrix diffusion. The purpose is to investigate to what degree matrix diffusion and related contaminant condition proximal to the Main Street DAPL pool may preclude technically and economically practicable remedial alternatives. The location to be studied must be the area at the source, not some distant location where NDMA is present at extremely low concentrations (e.g., GW-405BR) or a location with markedly dissimilar geology (e.g., GW-202BR). Olin never advocated GW-405BR as a suitable location. GW-406BR was used as an example for discussion purposes since we believe the degree of fracturing in that borehole will be similar to conditions on the down gradient side of the Main Street DAPL Pool within the Main Street Bedrock Saddle. Work is not proposed at GW-406BR. The technical basis for the selection of the proposed core hole was discussed in response to General Comment 1 above.

The duration of time a borehole is open is insignificant compared to the time scale required for matrix diffusion to impact rock matrix at distances and levels that would be detectable.

Specific Comment 6: Section 2.2 Problem Statement, Page 4, Footnote 1*; The footnote expands on the previous assertion suggesting similarity between the Eastern Woolen Mill site in Corina, ME and the Olin site. It should be noted that the chemicals of concern at Eastern Woolen Mill were primarily chlorinated benzene compounds, not the exotic nitrogen-containing organic compounds contaminating the Olin site. While perhaps having some similarities, the bedrock formations at the Eastern Woolen Mill are also different distinct rock units, hundreds of miles distant from the Olin site. Further comparisons are difficult now as it does not appear that the source areas at the Olin site have been as well characterized as those from the Eastern Woolen Mill site.*

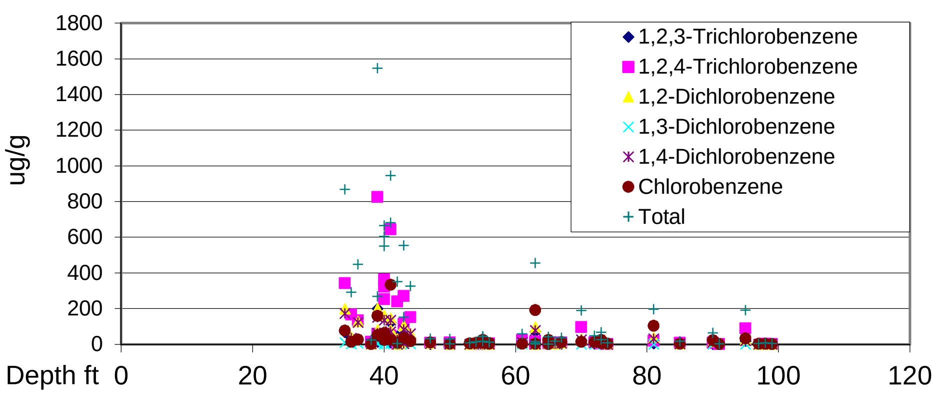
Response:

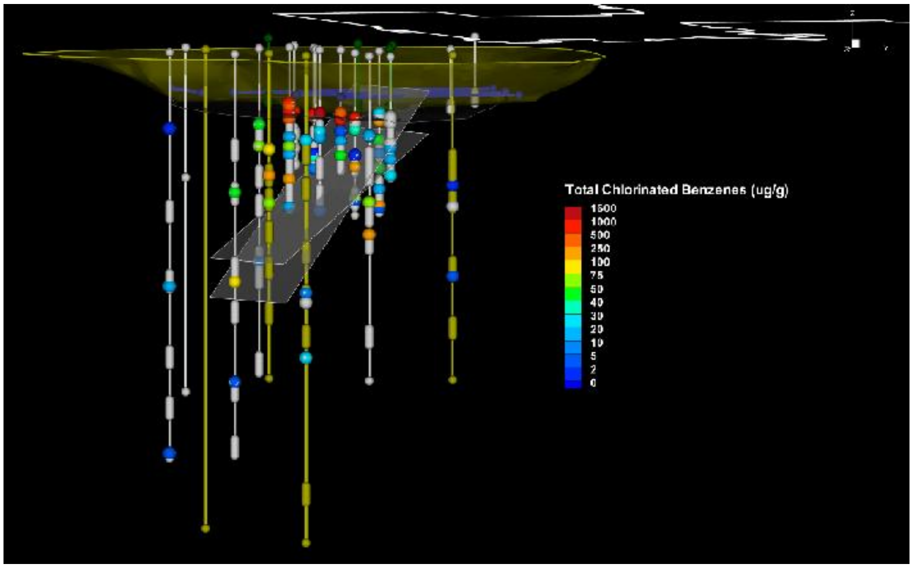
As you may be aware, the RI/FS for the Eastern Woolen Mill was prepared by Wood (Formerly HLA). The remedial design bedrock characterization was also conducted by Wood, but under contract to Nobis Engineering, the USEPA Remedial Action Contractor. As Wood is involved as a technical consultant at both Eastern Woolen Mill and Olin Chemical Superfund sites, we believe there are important similarities worthy of mention. As the diffusion coefficients for NDMA and chlorobenzene are very similar, the rate of matrix diffusion should be comparable; note, initial aqueous concentrations and the Koc for chlorobenzene compounds are greater than the same for NDMA. Although the rocks are different, they are both isoclinally folded metamorphosed sediments but with a different metamorphic grade (schist versus gneiss and amphibolite) and consequently the style of fracturing is quite similar. Both sites have weathered bedrock zones and numerous very small fractures which would potentially increase (as USEPA noted in its prior comments) contaminant storage capacity in the bedrock.

The detailed characterization of the Eastland Woolen Mill Site occurred as a remedial action design investigation after the ROD for OU1 was finalized. The early removal action under the NTCRA that was conducted concurrently with the RI prevented access to the source area to drill bedrock borings. Only one bedrock well had been installed near the source area prior to completing the RI/FS, Proposed Plan and ROD for OU1 (groundwater) for the Eastland Woolen Mill Site.

Exhibit 1 presents a graph and 3D graphic of rock matrix results for the shallow rotosonic borings at Eastern Woolen Mill site. (Up to 100 feet). Rock matrix samples were also collected from air-hammered borings and chlorinated benzene compounds were detected in rock matrix to a depth of 200 feet below the top of bedrock. Groundwater vertical gradients are upward at the site.

Exhibit 1. Chlorinated Benzene Rock Matrix Data from Shallow Bedrock Boreholes





Specific Comment 7: Section 2.3 Objective*; It remains unclear how the method selected will be able to resolve and discriminate between so-called "bedrock matrix" and so-called "zones of low transmissivity". How will the continuous measurement of transmissivity method be used alone or in conjunction with other methods to differentiate between true matrix transmissivity vs. zones of low transmissivity? Please clarify.*

Response:

Matrix transmissivity cannot be measured in this rock type with a FLUTe liner since the rocks have little primary porosity. Olin did not propose field measurements for or identify as an objective measurement of matrix transmissivity. The objective is to develop a transmissivity profile of the entire borehole to aid in the evaluation of a FLUTe system design, subject to the limitations inherent in the method and borehole conditions which are currently unknown.

Specific Comment 8: Section 2.3 Objective; Spatial Resolution *Spatial Resolution is discussed in passing in this section, but additional specificity is needed. For example, it is stated that, "In order to better understand flow and consequently contaminant transport at a smaller scale in DFNs, testing of aquifer properties should be conducted with high spatial resolution where deemed economically and technically feasible. In 2014, Keller (Keller, Cherry and Parker, 2014) published a new approach for continuous measurement of transmissivity in bedrock boreholes which provides high spatial resolution based on work conducted over the previous decade. This method has been widely used in the industry to estimate transmissivities in bedrock boreholes." What will be the expected vertical resolution on transmissivity using the "continuous" method? Please provide site-specific examples of "high spatial resolution based on work conducted over the previous decade", including the effective resolution of contaminant diffusion into matrix calculated in these examples. It is noted in the following section that rock core will be sampled at a 1-foot interval. As such, there may be little added value for higher resolution 'continuous' transmissivity data, even if this is* *possible to obtain. To more tightly constrain distance estimates of matrix diffusion into "matrix", a finer degree of spatial resolution may be needed. Additional discussions are warranted.*

Response:

Prior to installing a FLUTe system a blank liner will be installed to seal the boring to prevent gradient driven cross contamination in the borehole. The continuous transmissivity profile is completed during that process. As part of the revised CSM, it will be useful to understand to what degree the weakly fractured bedrock is transmissive. Using NDMA results of groundwater samples, it will also allow estimates of mass flux in groundwater from bedrock zones where matrix samples were collected and analyzed. An example of low resolution hydraulic testing would be an open borehole/large volume slug test since it says little about where the water is coming from. Higher resolution could entail packer testing of individual zones. The highest resolution possible is a continuous profile. The referenced article is attached.

The FLUTe Transmissivity Profiling was added by Parker, Cherry and Chapman to the DFN approach in 2012.

Specific Comment 9: Section 3.1 - Bedrock Coring, Rock Matrix Sampling and Analyses
The text states that, "*The core will be processed at one-foot intervals by crushing the core; and samples of the crushed rock will be collected preserved, and prepared for laboratory analysis.*" Why was a 1-foot level of discretization chosen? To more tightly constrain distance estimates of matrix diffusion into "matrix", a finer degree of spatial resolution may be needed. Additional discussions are warranted.

Response:
Please see response to General Comment 1.

Section 3.1.1 – Bedrock Coring and Sample Preparation; *¶ 1; The text states, "a nine-inch diameter casing will be sonically advanced to the top of bedrock and an additional five feet into bedrock to set the casing. At that terminal depth, a six-inch diameter permanent steel casing will be installed and tremie- grouted to grade. Following curing, the borehole will be cored to an additional 150 feet into bedrock, using HQ wireline coring techniques using five-foot length triple tube core barrels. Core will be logged and documented in field data records consistent with the approved RI/FS Work Plan (MACTEC, 2009)". Additional discussions are needed on many of the items listed in this paragraph. How will it be insured that five feet into bedrock will result an effective seal of the 6-inch casing. This should be the performance objective, not simply a specific length of casing into the bedrock. Please provide alternative language indicated what measures will be taken to ensure that the 6-inch casing is effective in sealing off potentially contaminated waters from higher levels from contaminating the open borehole resulting from the coring process. Also, please provide specific language from the "approved RI/FS workplan" which indicates that the standard core logging and field documentation procedures will result in the desired degree of resolution in terms of fracture* *identification, etc. How will features identified during the core logging process be used to differentiate between "matrix" and low-transmissivity (fractured) intervals? What degree of resolution is expected? Possible? More importantly, is it even possible to control recirculation drilling water during the coring process in a way that prevents cross contamination in the vertical dimension? Please clarify.*

Response:

The work plan provided a general statement how casing will be set. The distance at which the casing will be set will be determined in the field during boring installation. The work plan will be modified to reflect this. The casing will be set in rock both the driller and the geologist feel will provide an adequate seal for coring. Weathered bedrock above that seal will be sampled directly for the sonic core if required.

Specific Comment 10: Section 3.1.1 - Bedrock Coring and Sampling Preparation*; The text states, "Samples of the core will be collected and processed at one-foot intervals by using the widely-recognized CORE DFN methodology (developed by Parker), which uses proprietary equipment and procedures licensed by the drilling subcontractor (Cascade). The method involves use of specially designed equipment to crush the rock core and transfer the crushed sample to the sample container with minimal exposure to atmosphere. All core samples will be prepared for laboratory analysis on site, including, crushing and preservation in provided glassware. Other routine field activities (e.g., QA/QC samples at 20% frequency, field duplicates, record keeping, database management, and decontamination), will be performed as outlined in the approved 2009 Work Plan." There are many aspects to items listed in this paragraph which will require further detail and vetting. While it is stated that the "approved 2009 Work Plan" addresses "routine field activities", it appears as most of the activities involved in the complex CORE DFN approach are non-routine, and involve proprietary equipment and methods. Considering this dichotomy, additional information is needed. It is suggested that a table is created which tabulates the following information:*

- *Region 1 sites where CORE DFN has been used*
- *COCs of interest at those sites.*
- *Other sites in the U.S. where CORE DFN has been used to assess NDMA*
- *Level of vertical discretization (core processing interval)*
- *Number of boreholes per site*
- *Total feet of core collected/analyzed at each site*

Response:

The CORE DFN approach advocates combining a series of investigation technologies that have been in existence for many years into a unified investigation system or methodology. USEPA itself conducted rock matrix sampling (then called Methanol Extracted Rock Chip or MERC sampling) at the Quarry Site adapted from methods developed by Wood (Formerly HLA) at Loring AFB in

Limestone, Maine and has first-hand experience with rock matrix sampling (USEPA, 2005). USEPA, in its report, concluded the MERC sampling method showed good reproducibility based on duplicate sample results. That characterization effort by USEPA for a steam pilot test, also employed borehole geophysics, straddle packer transmissivity testing, including developing transmissivity profiles and inter-well testing. The characterization work by USEPA encompassed many of the elements of the CORE DFN approach. The same can be said for characterization efforts at Eastland Woolen Mill Superfund Site which included installation of a FLUTe system as early as 2001. USEPA has had experience with this methodology for almost two decades.

USEPA's request that we develop a list of all sites where these methods have been used in Region 1 and across the country, with a list of COCs, vertical discretization, number of boreholes and total feet of core collected is an unreasonable request. These are not innovative technologies. They have been standard practice (which EPA is familiar with, as discussed above) from more than a decade. To be clear, we are not aware of any sites that have attempted to characterize NDMA presence or absence in rock matrix. But we have successfully analyzed chlorinated ethenes and ethanes, chlorinated benzenes, and perfluorinated alkyl substances (PFAS) in various rock matrices including basalt, siltstones/mudstones, metamorphosed sedimentary rock and limestone.

The proprietary aspects that Stone Environmental licensed from Dr. Parker and which were later acquired by Cascade through its acquisition of Stone included the developed mobile laboratory microwave extraction technique for VOCs in rock matrices and the core crushing apparatus that minimized loss of VOCs from processed samples. We are not using the microwave extraction method since the fixed laboratory who conducts NDMA analysis for the project was concerned about unknown effects of microwave on the NDMA molecular structure. Since NDMA is not volatile the proprietary core crushing apparatus is not essential, but certainly better suited for processing core than by other less developed means. As discussed above the remaining methods used in the CORE DFN approach are neither proprietary nor innovative including diamond bit coring, borehole geophysics, transmissivity profiling, or use of a FLUTe liner as a multilevel monitoring device. The proposed use of the FLUTe liner under a vacuum is new but well within the technical application of the device. We have spoken with Carl Keller (developer and owner of FLUTe) concerning our proposed use of the Water FLUTe system and he is quite confident it can be implemented and is willing to assist with design considerations once data has been collected.

In summary we believe that very few of the field activities proposed are non-routine or proprietary. We believe an exhaustive literature review as requested is unwarranted.

Specific Comment 12 Section 3.1.3 – Sample Extraction and Analysis; *"The need for use of a drying agent (sodium sulfate or equivalent) will be determined based on the characteristic of the crushed rock media. If moisture is observed in the sample, the drying agent will be applied and stirred into the rock using similar procedures as is done for soil samples. The laboratory will add the extraction solvent dichloromethane (methylene chloride) to the rock chip samples." It stands to reason that if chemicals have diffused into the rock matrix, then water, which has been present* *throughout the system for centuries, is also present within the core matrix. As such, drying agent should be considered in all cases? Please clarify. Also, please provide additional information which supports the use of methylene chloride as appropriate for extracting NDMA from the rock matrix. Please provide case histories from other sites where the CORE DFN approach has been used to assess NDMA matrix diffusion.*

Response:

A drying agent is a common application to remove excess free liquid from the surface of solid matrix samples. It is not intended to remove pore water. Application of a drying agent would be a laboratory decision.

Methylene chloride is the standard solvent used for the NDMA low level method for solid matrices including soils and is the solvent for liquid-liquid extractions. We have selected methylene chloride to be consistent with the approved standard method. Methanol and DI water were also considered as viable extractants but offered no clear advantage.

Specific Comment 13: Section 3.2 – Borehole Structure and Hydraulic Characterization
Please provide the SOPs which describe procedures to be used to account for drilling water lost to the formation during drilling operations. It is presumed that at least as much water as was taken by the borehole during drilling will be removed prior to further testing. Please clarify intention, approaches, and controls in this regard. Consideration should be given to tagging the drilling water with a tracer to ensure that it has all been removed prior to subsequent testing. Also, as noted above, what steps can be taken to control recirculation drilling water during the coring process in a way that prevents cross contamination in the vertical dimension? Please clarify.

Response:

Drilling water use is noted and tabulated by the rig geologist in the field log book. There is no specific SOP for this data record. There is no drilling method that does not disturb the groundwater system around the borehole. There is no practical way to inhibit vertical communication of water in the borehole. In fact, it is an essential element of drilling since the cutting must be flushed from the borehole as the drill bit is advanced. If is often impractical to remove the volume of drilling water during well development, which is the basis for waiting several days after conventional well installations before sampling. This waiting period allows the groundwater to move down gradient beyond the well by advective flow.

With regard to tracers, the Town of Wilmington uses chloramine as a disinfectant and therefore fluoride is not present in the public water supply. Both bromide and fluoride are present in DAPL at concentrations up to 33 and 53 mg/L respectively. The Hach meters, which would be used for in-field testing report chloride and iron as positive interferences for bromide. Fluorescene loses much of it fluorescence at pH below 5. Therefore, there does not appear to be a simple option for tagging the drilling water due to the chemistry of DAPL and diffuse groundwater.

Based on other bedrock wells installed near the DAPL pools, we expect to encounter diffuse groundwater and therefore monitoring specific conductivity with time in the field will provide a reliable field indicator for when groundwater conditions have re-equilibrated after drilling disturbances.

Specific Comment 14: Section 3.2 – Low Transmissivity Bedrock Groundwater Sampling and Analysis *The proposed approach focusses on using a FLUTe liner to assess low transmissivity portion of the bedrock. However, it is not clear how this information will be evaluated in conjunction with the packer samples proposed for collection in the previous step which indicates that these packer samples will be considered as "screening level data, since there will be limited time for the borehole to re-equilibrate after drilling." What will be the effects on the study if the screening level packer results are erroneous? How will this be determined once the FLUTe liner is installed? This aspect of the draft work plan bears re-thinking.*

Response:

We have considered that aspect of timing and purposely used the term "screening level" to alert the reviewers of this consideration. When the packer sampling is being implemented, specific conductance will be monitored and plotted when the packer zone is being purged. If it does not appear specific conductance is stabilizing and is low compared to expected values from MP-4, it is likely the groundwater is still being affected by drilling waters. If that is the case then a second set of packer samples can be collected between removing the blank liner and installing the FLUTe system. The time duration the blank liner will be in place will allow remaining drilling water to be removed by advection from the vicinity of the well.

The advantage of FLUTe system is that they can always be removed to allow access to the borehole. In addition the FLUTe system, which can accommodate 4 ports in this diameter core boring can be designed to monitor both high and low K fracture zones if the project team decides this is necessary.

Additional References

Parker, B, Gilham, R., Cherry, J., Diffusive Disappearance of Immiscible – Phase Organic Liquids in Fractured Geologic Media. Ground Water 32(5)

Parker B, McWhorter, D., Cherry J., Diffusive Loss of Non-Aqueous Phase Liquids in Fracture Networks in Geologic Media. Ground Water 35(6)

Attachments

1. Discrete Fracture Network Approach for Studying Contamination in Fractured Rock. Beth Parker, John Cherry and Steve Chapman. Aqua mundi 2012.
2. New Method for Continuous Transmissivity Profiling in Fractured Rock. Carl Keller, John Cherry and Beth Parker. Ground Water 2013

Attachment 1

Beth Parker, John Cherry and Steve Chapman. Discrete Fracture Network Approach for Studying Contamination in Fractured Rock. Aqua mundi 2012

Discrete Fracture Network Approach for Studying Contamination in Fractured Rock

Beth L. Parker, John A. Cherry and Steven W. Chapman

Abstract: A comprehensive methodology, referred to as the Discrete Fracture Network (DFN) approach for investigating contaminated sites on fractured sedimentary rock has evolved through intensive studies at several industrial sites contaminated with chlorinated solvents. The approach is directed at acquiring complementary datasets from cored holes with many diverse types of measurements, including core analyses of contaminant distribution and physical, chemical and microbial properties of the matrix, and also corehole tests focused on the nature of the fracture system. Ultimately the goal of this approach is to acquire field and laboratory data necessary for application of DFN numerical models for simulation of groundwater flow and contaminant transport and fate incorporating relevant controlling processes. These studies have provided the basis for development of a general conceptual model for contaminant behavior in fractured sedimentary rock wherein the matrix porosity (typically 2-20%) provides large storage for dissolved and sorbed phase contaminants. Diffusion has driven contaminant mass from the fractures where active groundwater flow occurs into the low permeability rock matrix blocks. This mass transfer combined with the aged nature of these sites results in nearly all contaminant mass now residing in the rock matrix. The fracture networks are also shown to be dense and interconnected which enhances contact between fractures and matrix. As a consequence the resulting contaminant plumes are orderly and small relative to what would be expected from large groundwater velocities in the fractures. The limited plume extent is due to strong matrix diffusion with sorption, transverse lateral spreading in fracture networks and in some zones, contaminant degradation. These processes can be represented in DFN model simulations which have been shown to generate simulated plume conditions that represent the style of contaminant distributions and magnitude of plume attenuation when informed and constrained by site-specific parameters obtained using the DFN approach..

Keywords: fracture networks, sedimentary rock, site characterization, chlorinated solvents, diffusion, solute transport

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Riassunto: *L'articolo tratta di una metodologia integrata per investigare i siti contaminati localizzati su rocce sedimentarie fratturate, denominata "approccio DFN (Discrete Fracture Network), la metodologia viene sviluppata a partire da indagini approfondite, condotte su 8 siti industriali contaminati, situati negli Stati Uniti ed in Canada. L'approccio è una combinazione di metodi di campo, di cui molti sono innovativi e pochi sono miglioramenti di tecniche consolidate e considerate già mature; la fase di affinamento dell'approccio è ancora in corso. L'approccio è diretto ad acquisire data-set integrati di parametri, tramite vari tipi di misure, a partire da carotaggi. Tali misure possono riguardare sia le carote prelevate, comprendendo analisi dei contaminanti e delle proprietà fisiche, chimiche e biologiche della matrice rocciosa, sia il foro di sondaggio, focalizzandosi sulla natura del sistema di fratture e delle sue interazioni con la matrice. I data-set ottenibili da ogni foro sono assai diversi per tipologia e quantità di informazioni; per tale motivo è stato creato un sistema informativo relazionale di immagazzinamento e gestione del dato al fine di facilitare le procedure di QA/QC e di favorire la trasparenza e la tracciabilità. Il fine ultimo di questo approccio è quello di acquisire i dati di campo e di laboratorio necessari per l'implementazione di modelli numerici DFN, in primo luogo modelli statici avanzati (es. Petrel) ed in secondo luogo modelli dinamici (es. FRACTRAN, HydroGeoSphere) ai fini della simulazione del flusso di falda e del trasporto e destino dei contaminanti. Tutti i parametri necessari per la caratterizzazione delle fratture e della matrice rocciosa sono misurati secondo una o più modalità usando sia le carote che il foro, ad eccezione della lunghezza delle fratture. Le distribuzioni della lunghezza delle fratture sono inferite dall'analisi di dettaglio della distribuzione dei contaminanti, impiegando sia l'osservazione diretta nelle carote sia la simulazione calibrata con approccio DFN; in quest'ultima la conducibilità idraulica media dell'ammasso è assegnata in prima istanza a partire dall'analisi di prove di pompaggio e successivamente calibrata tramite simulazioni numeriche tridimensionali di flusso con approccio EPM (Equivalent Porous Medium). Rocce sedimentarie densamente fratturate rappresentano il substrato geologico degli 8 siti indagati, tutti contaminati da inquinanti organici, per lo più solventi clorurati. La porosità della matrice di queste rocce (arenarie, siltiti, argilliti o dolomie), tipicamente compresa fra il 2 ed il 20%, agisce da grosso volume di immagazzinamento per i contaminanti in fase disciolta. La diffusione ha guidato il trasporto di massa di contaminante dalle fratture, laddove avviene un flusso attivo di falda, verso i blocchi di matrice a bassa permeabilità. Questo trasferimento di massa, combinato alla lunga storia della contaminazione di questi siti, ha fatto sì che quasi tutta la massa del contaminante ora risieda entro la matrice rocciosa. I plume di contaminazione che ne risultano sono regolari di forma e piccoli rispetto a quanto ci si sarebbe potuto aspettare sulla base della elevata velocità di flusso associata alle fratture. La limitata estensione dei plume è dovuta alla forte diffusione nella matrice, associata ad adsorbimento, oltre che alla migrazione laterale trasversale nella rete di fratture e, in alcuni siti, alla degradazione dei contaminanti. L'applicazione di modelli di trasporto bi-dimensionali di tipo DFN, che incorporano i processi rilevanti che coinvolgono sia le fratture che la matrice, forniscono la base per quantificare i fenomeni suddetti. Laddove implementati e calibrati tramite parametri sito-specifici ottenuti tramite l'approccio DFN e tramite codici numerici tridimensionali di flusso di tipo EPM, i modelli DFN sono stati impiegati per generare plume simulati che rappresentino la distribuzionedella contaminazione e quantifichino l'attenuazione naturale.*

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Introduction

Groundwater flow analysis in fractured rock is most commonly addressed using the ‘equivalent porous medium’ (EPM) assumption, which is satisfactory for many types of flow problems. However for assessment of contaminant transport and fate, approaches based on discrete fracture network (DFN) concepts are generally necessary (NRC, 1996; Lapcevic et al., 1999; Berkowitz, 2002). Nearly 15 years ago a major field focused program aimed at improved investigation methods for delineating and understanding the evolution of organic contaminant source zones and plume fate and transport in fractured sedimentary rock was initiated at the University of Waterloo, and since 2007 the program has been based at the University of Guelph. The field efforts began in 1996, when intensive studies were initiated at a TCE contaminated site on steeply dipping and faulted sandstone near Simi Valley, California. Now, with collaborations involving several disciplines (analytical chemistry, mathematical modeling, geophysics, microbiology) the program includes seven additional sites contaminated primarily with chlorinated solvents (Table 1): a Wisconsin site on flat-lying sandstone and dolostone, two sites in New York State and one in New Jersey on siltstone and shale and three sites in Ontario on flat-lying dolostone. These sites have important differences so overall are broadly representative of sedimentary rock, but also several aspects in common including: much data from earlier conventional investigations, contamination initially caused decades ago by DNAPL and therefore these are ‘aged’ sites, sufficient matrix porosity (2-20%) allowing diffusion-driven chemical mass transfer between fractures and the rock matrix causing strong influence on contaminant behavior, and each site receives much regulatory attention. Diffusion and other processes have caused the plume fronts to advance at rates much slower than groundwater velocities in the fracture networks (Figure 1).

From this research a comprehensive approach has evolved, referred to as the Discrete Fracture Network (DFN) Approach, for investigating sites on sedimentary rock such as sandstone, siltstone, shale, limestone and dolostone. This research has resulted in development of a general conceptual model for the formation and long-term evolution of source zones and plumes in fractured sedimentary rock (Figure 1). Nearly all sedimentary rock has substantial effective matrix porosity (generally 2-20%) allowing contaminant mass to readily diffuse into the matrix in the early decades of contamination, and out of the matrix in later decades or centuries. Although it is typical that nearly all groundwater flow occurs in the fracture network, at ‘aged’ contaminated sites most contaminant mass now resides in the much lower permeability matrix blocks between fractures. Therefore, the DFN Approach emphasizes using rock core to delineate the contaminant distributions in the matrix and on investigations of the fracture network. Although the DFN Approach had been developed specifically for sedimentary rock, it is relevant to all rock types; however, the rock core sampling approach must be adjusted to suit the nature of the matrix porosity, sorption, contaminant type and time for diffusion. Conventional approaches for investigating fractured sedimentary rock are inadequate because they are biased toward answering questions most relevant to groundwater quantity and water supply. Therefore, the rock matrix is ignored and most of the fractures with active flow and transport go unrecognized. The lack of rock core contaminant data makes it generally impossible for conventional studies to characterize plumes in fractured porous rock.

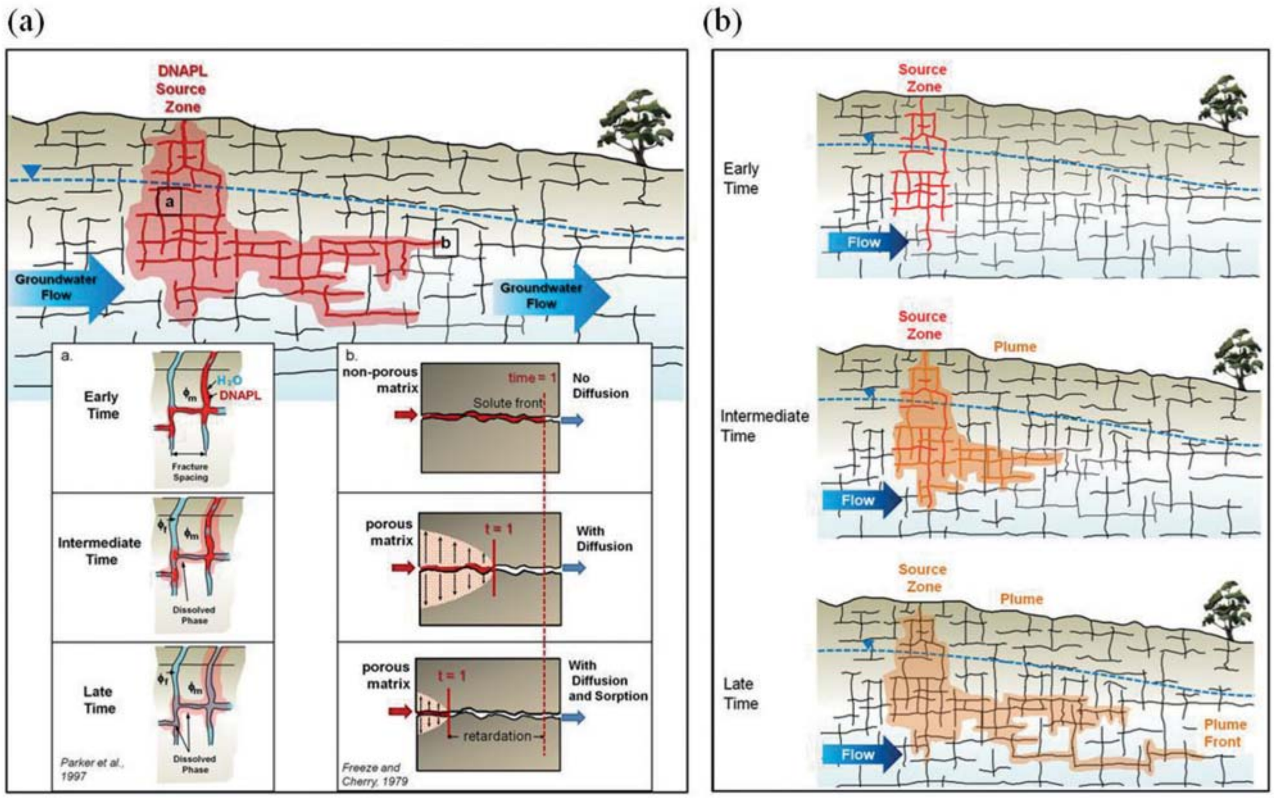

Fig. 1*: Conceptualization of source zone and plume evolution in fractured sedimentary rock: (a) schematic cross-section showing DNAPL release with formation of a downgradient plume, with insets showing source zone evolution (adapted from Parker et al., 1997) and diffusion effects on contaminant migration (adapted from Freeze and Cherry, 1979), and (b) conceptual stages of source zone and plume evolution (adapted from Parker et al., 2010).*

History of DFN Models and Analysis

It is essential in the DFN approach that the methods and models view the rock as having a network of discrete fractures where the spacing, length, orientations, apertures and related hydraulic head distributions and permeability are the focus of field measurements. The earliest origins of many of these measurement methods lie in geotechnical engineering. Snow (1965) introduced the Cubic Law to estimate hydraulic aperture values from hydraulic tests in boreholes, with a goal of determining the interconnected fracture void space related to grouting at dam sites. To account for atmospheric tritium distributions in fractured chalk in the UK, Foster (1975) introduced the concept of diffusion-driven mass transfer from discrete fractures, where nearly all flow occurs, into the low permeability rock matrix blocks between fractures. For fractured porous media including sedimentary rock and fractured clayey deposits, Freeze and Cherry (1979) drew attention to the broader importance of matrix diffusion involving discrete fractures in contaminant hydrogeology. Gale (1982) drew attention to the need to do hydraulic testing in a manner that provides insight concerning fracture hydraulic properties. Concepts for contaminant transport in fractured geologic media where the matrix has substantial interconnected porosity were advanced earliest through investigations in fractured, non-indurated clayey deposits where it was relatively easy to conduct experiments and monitor contaminant migration in shallow zones (<10 m) (e.g. McKay et al., 1993) during field experiments and use large cylindrical soil columns extracted from excavations for laboratory experiments (e.g. Grisak et al., 1980). These fractured clay environments served as close analogs for fractured sedimentary rock.

The first multilevel monitoring system (Westbay) for obtaining detailed profiles of water pressure (head) in rock boreholes was developed for study of mountain slope stability, where it is necessary to know the locations of the porewater pressures most conducive to slope instability. Later this system was adapted for groundwater contamination studies (Black et al., 1986). Also in the 1980s borehole geophysics advanced markedly, with borehole televiewing as a means of 'seeing' fractures becoming important in fractured rock site studies. It was not until the 1980s that mathematical models for groundwater flow and contaminant transport in discrete fracture networks achieved major advances driven mainly by the need to predict radionuclide transport in discretely fractured crystalline rock (e.g. Rouleau, 1984; Long and Billaux, 1987; NRC, 1996). Beginning in the early 1990s, numerical models incorporating random fracture networks and also matrix diffusion became available (e.g. Sudicky and McLaren, 1992; Therrien and Sudicky, 1996). However, although there was an immense effort internationally directed at predicting radionuclide transport in crystalline rock, and through this effort DFN concepts and some field methods were strongly advanced, this effort lacked the opportunity to investigate actual contaminant plumes because the deep rock repositories that were the focus of the effort were only conceptual; no such repositories and no actual radionuclide plumes existed for model verifications.

General Conceptual Model

The development of the DFN approach for investigating contaminated sites on sedimentary bedrock began with an initial conceptual model for contaminant distributions and behavior. This conceptual model, displayed in Figure 1, was based on the premise that, at sites where the contaminants have been in the rock for many years or decades, diffusion-driven chemical mass transfer has caused much or nearly all of the contaminant mass to be relocated from fractures, where nearly all groundwater and non -aqueous phase liquids (NAPL) flow occurs, into the low permeability rock matrix blocks between the fractures, where groundwater is essentially stagnant. This initial conceptual model was based on analytic (Parker et al., 1994; 1997) and numerical modeling (Vanderkwaak and Sudicky, 1996) of chlorinated solvent DNAPL dissolution and diffusion effects and expectations for plume evolution in fracture networks in porous rock with representative rock matrix properties. Based on this model, the goal of determining the contaminant mass distribution must be accomplished by determining the contaminant mass present in low permeability rock matrix blocks between the fractures.

DFN Field Approach Development and Components

The DFN field approach, which was first applied in 1996 at a site near Simi Valley, California on interbedded sandstone and shale, is now well demonstrated in the US and Canada. To date it has been comprehensively applied at eight contaminated sites in sedimentary bedrock including sandstone (2), dolostone (3), shale (2) and siltstone (1) where chlorinated VOCs are the primary contaminants of concern (Table 1). At these sites the contaminants act as tracers of the flow system and transport processes occurring over several decades under natural gradient conditions. Investigations are continuing at most of these sites. The information collected from these eight sites forms much of the supporting basis for the general conceptual model for contaminant plumes from 'point sources' in fractured sedimentary rock (Figure 1). The DFN Approach was developed to take advantage of numerical models that became available in the 1990s for simulation of groundwater flow and contaminant transport in discrete fracture networks with porous rock matrix blocks between fractures (e.g. Sudicky and McLaren, 1992; Therrien and Sudicky, 1996). Previously, these models had not been used to represent real-site conditions due to the lack of suitable field data. The DFN approach combines field data and numerical model application to advance site conceptual models (SCMs) that can serve as the basis for contaminated site decision-making regarding contaminant fate, assessment of risk to receptors and evaluating remediation feasibility and designs. This approach is based on the premise that characterization of contaminated sites and SCM development should be separate from, and prerequisite to, design of long-term monitoring networks.

The following major categories of activities constitute the DFN Approach:

1. rock core chemical analyses and rock matrix properties,
2. use of liners for sealing boreholes and transmissivity measurements,
3. high resolution temperature profiling in sealed holes for identifying hydraulically active fractures without effect of borehole cross-connection,
4. borehole geophysics for rock properties and fracture conditions,
5. straddle-packer hydraulic testing,
6. high-resolution multilevel monitoring systems for hydraulic head and groundwater sampling,
7. data storage/management in a comprehensive relational database system, and
8. static and dynamic modeling.

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Tab. 1: *Summary of eight sites where the DFN approach is being extensively applied.*

Site	Location	Water Supply Aquifer?	Rock Type	Major Parent Chemicals	Degradation Products	Approximate Release Period	Water Table Depth (m bgs)	Maximum Contaminant Depth (m bgs)	Overburden Thickness and Type (m)	Cause of Contamination and comments
1	Simi, California	No	sandstone with siltstone and shale interbeds, 30° dip	TCE, minor TCA	cis-DCE, 1,1-DCE, trans-DCE, VC	1950s - 1960s	< 15 to 100 m	> 350 m	0 - 5 m; alluvium	Rocket engine testing, research; many plumes from many different source areas; no DNAPL found
2	Wisconsin	Yes	sandstone with minor siltstone and dolostone; flat lying	PCE, TCE, TCA, ketones	cis-DCE, 1,1-DCA, 1,1-DCE, VC	1950s - 1960s	0 - 25 m	most mass < 60 m (max <100 m)	5 - 40 m; glacial sand, silt and clay layers	Solvent recycling; 10,000 gal DNAPL pumped from source zone, residual DNAPL remains
3	South Plainfield, New Jersey	Yes	mudstone; 5-15° dip	PCE, TCE, PCBs	cis-DCE, VC	Facility operating since 1920s; release period unknown	< 3 m	> 120 m	0.1 - 5 m; Glacial deposits (reddish brown silt, sand and clay); fill in some areas	Manufacturing; auto industry parts and electronics; DNAPL observed in one well
4	Watervliet, New York	No	shale, 50° dip	PCE, TCE	cis-DCE, trans-DCE, VC	Facility operating since early 1800's; likely 1950s -1960s for studied plume	<6 m	> 50 m	3 -6 m; Glacial deposits (dark grey silty sand and gravel)	Manufacturing; military (oldest cannon manufacturing facility in the US); focus on one plume; DNAPL observed in one well in 1990s
5	Union, New York	Yes (private wells)	siltstone with minor sandstone and shale	TCE, petroleum products	cis-DCE, VC	1950s - 1970s	< 2 to 7 m	most mass < 6 m (max < 15 m)	< 2 m; Glacial deposits (sand and silt)	Chemical disposal in burn pits from off-site manufacturing and lab operations
6	Cambridge, Ontario	Yes	dolostone aquifer overlying shale aquitard; flat lying	Metolachlor, TCE, minor PCE	cis-DCE and metalochlor deg products	1978 - 1990	~20 m	150 m (into shale aquitard)	25 - 40 m; Glacial deposits (sand and silt, thin basal till over bedrock)	Agricultural chemical packaging; no DNAPL found
7	Guelph, Ontario	Yes	dolostone aquifer overlying shale aquitard; flat lying	TCE, minor PCE	cis-DCE, VC	1990s	3 - 5 m	> 100 m	3 - 6 m; Glacial till	Manufacturing; auto parts; no DNAPL found
8	Guelph, Ontario	Yes	dolostone aquifer overlying shale aquitard; flat lying	PCE	TCE, cis-DCE	1950s-1970s	3 - 5 m	>30 m	3 - 6 m; Glacial till and gravel backfill	Former dry cleaner; no DNAPL found

The flow chart in Figure 2 summarizes the many components of the DFN Approach; the left side displays observations and measurements made using rock core and the right side shows measurements made in the corehole. In each hole, the DFN Approach emphasizes determining all of the fractures through which groundwater flow occurs under ambient conditions. Results at eight sites on sedimentary bedrock show that contaminant distributions can be explained only if groundwater flow and contaminant transport occur in a multitude of interconnected fractures. Therefore, improved sensitivity for identifying hydraulic activity in as many fractures as possible under natural conditions is key. Table 2 provides an overview of the various techniques utilized in the DFN Approach, and each is described in more detail below. Some components of the DFN Approach continue to be refined and new methods identified; however, the results obtained to date from the eight field sites provide a well established suite of methods and insights for this science-based framework for decision making regarding the transport and fate of contaminants, remediation, and long-term monitoring. The approach is now sufficiently advanced for application at many more sites.

Two elements clearly distinguish the DFN Approach from conventional approaches: (1) use of rock core for contaminant analyses (Figure 3), and (2) use of flexible-impervious liners to (i) seal holes to prevent cross-connection, (ii) measure transmissivity profiles while the liner is installed, and (iii) allow high resolution temperature measurements inside the water filled liner to identify hydraulically active fractures while avoiding the masking effects of vertical connectivity. The DFN Approach avoids using data collected from partially or fully cross-connected open holes because such data tends to be misleading. To combat cross connection, emphasis is directed at minimizing the length of time the core hole is left open after drilling. Although the hole can be used for open-hole geophysics and hydraulic tests, the time allocated for open-hole data acquisition is purposefully limited. Immediately after the hole is drilled, a liner is installed using a procedure that provides transmissivity and hydraulic conductivity profiles (Keller et al., 2011). High resolution passive or active temperature profiling is then done inside the liner as a sensitive tracer of active groundwater flow in sealed (i.e. ambient) conditions (Pehme et al., 2010). The liner is removed for a short period at a later date to allow open-hole geophysical measurements and hydraulic tests. After the rock core and borehole data have been compiled and assessed, the liner is removed for the last time so a depth-discrete multilevel system (MLS) or conventional monitoring well can be installed, from which more data are acquired. These data are used as part of the site characterization, which includes assessment of various hypotheses and development of a robust site conceptual model (SCM). After the site characterization stage is complete, a long-term groundwater monitoring network is established based on the DFN datasets and the SCM. This system is then monitored at appropriate locations, depths and frequency over long periods of time to continue testing the SCM and provide confirmation of SCM predictions or early warning of unexpected impacts.

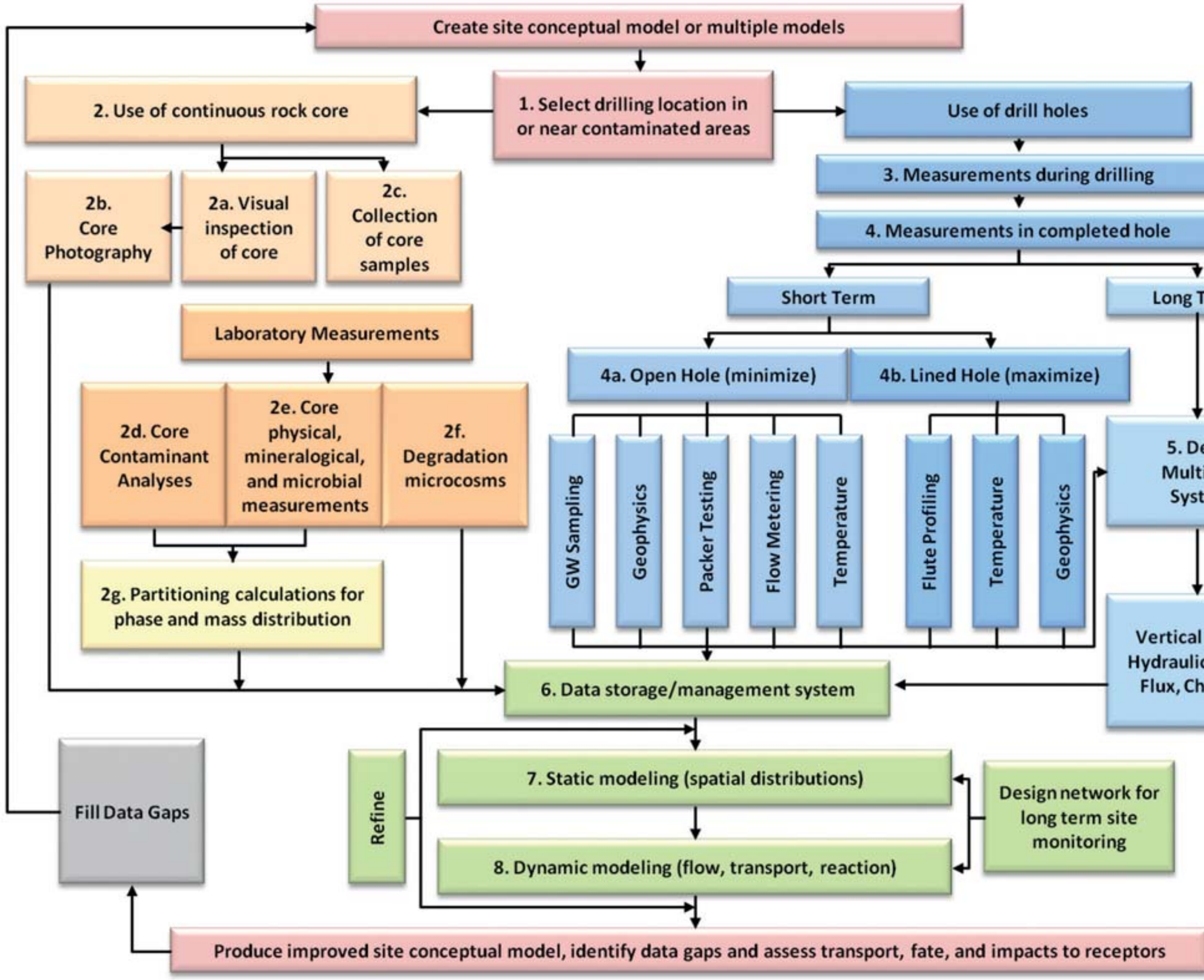

Fig. 2*: (The DFN approach uses both rock core and core hole derived dataset to characterize contaminated sites on fractured sedimentary rock.*

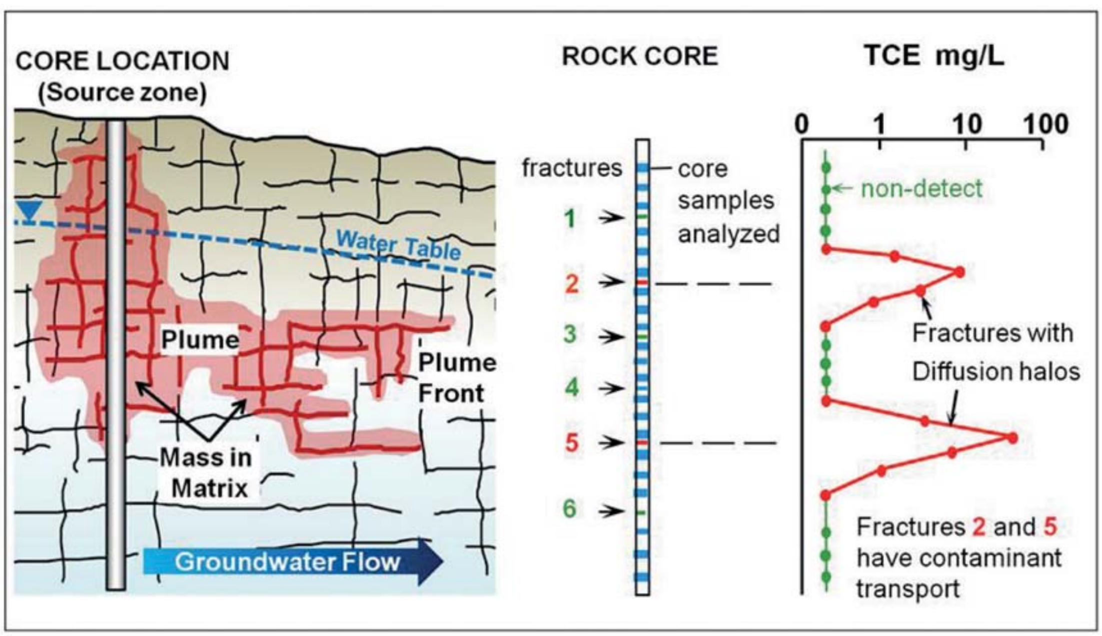

Fig. 3: *Rock core sampling approach and conceptual contaminant profile. Rock core profiles are used for identifying fractures where contaminant transport occurs and assessment of contaminant mass within the matrix..*

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Tab. 2: *Description of elements in the DFN approach following the flow chart (Figure 2). Minimization of the open hole methods refers to the need to minimize the time the hole is left open after drilling to reduce borehole cross connection and cross contamination.*

A Discrete Fracture network Approach (DFN) for Investigation of Contaminated Sites on Fractured Sedimentary Rock			
1	Drill continuous cored hole in or near area of suspected contamination, but not through zones of suspected free-phase DNAPL		
2	Use continuous rock core to determine contaminant mass distribution in rock, fracture spacing/orientation and matrix properties of the core relevant to contaminant mass storage and behaviour		
3	Measurements during drilling for insights about hydraulic head distributions and permeable zones		
4	Measurements in the completed hole to determine formation characteristic and groundwater flow		
	Activity	**Purpose**	**Description**
2a/b	Visual core inspection/ core photography	Geology/Fracture Identification	Texture, structures, minerals, bedding, fractures, coatings
2c	Core sampling	Lab analysis	Samples crushed/field preserved in methanol
2d	Contaminant analysis	Mass distributions	Crushed sample microwave extraction and VOC analysis of methanol extract
2e	Core properties	Understand behavior in matrix	Lab measurements of porosity, permeability, mineralogy, f_{oc}
2f	Core microbiology	Understand behavior in rock matrix	Microbe identification/characterization; microcosm degradation experiments
2g	Partitioning Calculations	Determine distribution in porewater and solids.	Use K_{oc}-f_{oc} based sorption estimates
4a Open Hole	Groundwater sampling	Understand cross contamination	Use discrete depth point sampler in the open water column
	Geophysics	Formation and fracture properties	Gamma, EM conductivity, image logs (ATV, OTV), Caliper
	Packer testing	Hydraulic conductivity	Up to four types of tests for good accuracy
	Flow metering	Cross connection assessment	Metering of vertical flow; heat pulse, EM or mechanical methods
	Temperature profiling	Cross connection assessment	High precision temperature measurements in flowing water column
4b FLUTe Lined Hole	Liner profiling	Measure K and T profiles	Profiles measured from rate of descent as the liner goes down the hole
	Temperature profiling	Identify hydraulically active fractures	High resolution temperature profiling in the static water column in lined hole with and without heating the water column
	Borehole geophysics	Formation rock properties and geology	Geophysical logging inside lined hole: gamma, EM conductivity, neutron, resistivity logging, etc.
5	Multilevel systems (MLS)	Obtain head profiles, water chemistry	Select commercially available MLS: Westbay, FLUTe, Waterloo-Solinst, CMT. Design positions of monitoring intervals and seals based on core and borehole data
6	Data storage system	Organize and store all data in a relational system	Organize QA/C, store all data in a relational database system, queryable to facilitate data interpretation
7	Static modeling	Display borehole data to facilitate interpretation	Use software such as WellCAD (1-D profiles) and ViewLog (1-D and 2-D) and PETREL (3-D) for log interpretation and spatial modeling
8	Dynamic Modeling	Simulate groundwater flow and contaminant transport	Simulate 3-D groundwater flow using FEFLOW or MODFLOW based on EPM assumption and DFN simulations of flow, transport and fate in 2-D using FRACTRAN, HydroGeoSphere

Role of Surface Observations

At some investigation sites, there is sufficient exposed bedrock for surface geologic observations to be useful or evidence of regional fracture (e.g. fault) systems that are visible at surface. For example, mapping of fractures and faults within the context of the surface geology can provide insightful information. Fracture length information cannot be obtained from boreholes but can at some sites be obtained from rock surface exposures examined on the ground and using aerial photography and satellite imagery. Therefore, at sites where rock outcrops exist, information from these outcrops is incorporated into the DFN approach. The other avenue for surface observations is surface measurements using geophysics. An exploration into the use of surface geophysical methods within the context of the DFN approach is in the early stage with the expectation that use of advanced surface geophysical methods may provide useful insights, primarily at sites where overburden covers the bedrock surface and at sites where the distribution of faults or other major structural features may need to be explored. Use of surface geophysics in the traditional role, to provide improved understanding of the bedrock surface and major structural features is well established however modern equipment and data inversion methods continues to advance capabilities. The value of surface geophysics for providing new insights concerning the nature and density of fractures in rock needs to be subjected to further research.

Rock Core Contaminant Analyses

he first step in the application of the DFN Approach at aged contaminated sites is to drill continuously cored holes and take numerous, closely spaced samples from the core for laboratory analysis of contaminant concentrations and physical and chemical properties after detailed visual inspection and logging of rock and fracture characteristics (Figure 3). Use of this method to determine fractures where contaminant transport occurs, and contaminant mass and phase distributions, is essential rather than only relying on data from monitoring wells to determine contaminant nature and extent. Monitoring wells or multilevel monitoring systems are generally not effective for comprehensive site characterization because they only sample groundwater from the fractures and not the rock matrix where nearly all contaminant mass resides. Also, samples from monitoring wells are prone to the influence of cross contamination due to open hole conditions or long well screens. Rock core contaminant analyses are done on small sections of rock collected along the entire length/depth of the core with an average 0.3 m spacing resulting in high resolution determination of the contaminant mass distributions. This average spacing is typical for sedimentary rock, such as sandstone, limestone and dolostone, where the primary contaminants have minimal sorption. The deepest hole where this method has been applied is 450 m. At sites where contaminant diffusion into the matrix is expected to be more limited, due to shorter times since the contaminants entered the systems or given matrix properties such as lower porosity or more sorption, sample spacing is more focused near fractures. Each contaminant category (e.g. volatiles, semi-volatiles, non-volatiles, metals) requires specific procedures for sampling, preservation, processing, and analysis. The rock core chemical analyses provide total contaminant mass and these are converted via calculation into dissolved and sorbed fractions as appropriate. Rock core samples are also retained for physical (e.g. porosity, permeability, diffusion coefficient), geochemical (e.g., mineralogy, organic carbon content) and microbial characterization. For sedimentary rock, the analysis typically shows nearly all contaminant mass occurs in the low permeability rock matrix as a result of diffusion from the fractures into the matrix over years or decades. The typical small rock matrix permeability limits disturbance of contamination in the matrix during drilling; however the extent of DNAPL must be considered and incorporated into drilling plans to prevent possible cross-connection and downward mobilization. Most of the studied sites have evolved to non-DNAPL conditions so that there are no rock core concentrations are above or close to solubility. Therefore, under these conditions downward mobilization of DNAPL is no longer an issue and holes are drilled through former DNAPL zones (Parker et al., 1994, 1997). Although the core hole is used for complementary methods to further understanding of groundwater flow and contaminant distribution after the core has been removed, it is the rock core contaminant results in the DFN Approach which guide application of these other methods. The field and laboratory procedures for collecting and analyzing rock core contaminant concentrations have been transferred to the commercial sector (referred to as the CORE DFN™ Approach).

Impermeable Flexible Liner (FLUTe™) Technologies

In the contaminated zone, the next step in the DFN approach immediately after drilling the hole is complete is creation of a borehole seal using a flexible impervious liner. Several methods in the DFN Approach involve removable ‘flexible liners’, referred to as FLUTe™ technologies. Collaborations have been ongoing with the developer of these technologies since 1997 to test, demonstrate and extend their unique capabilities for investigations in fractured rock. A ‘liner’ is an impervious fabric ‘sleeve’ installed in boreholes by eversion with water, such that the sleeve ‘lines’ the hole forming a tight seal. This liner serves as a continuous inflated packer, preventing hydraulic cross-connection in the hole, caused by water flowing into the hole from some fractures and then moving up or down the hole to exit from other fractures. In areas where groundwater contamination exists in the bedrock, this cross-connecting flow causes chemical cross-contamination that confuses monitoring well data interpretation and commonly alters the pre-drilling contaminant distribution (Sterling et al., 2005). Therefore, in some jurisdictions of North America (e.g. New Jersey) regulations for contaminated site investigations now require that soon after a hole is drilled, it must be temporarily sealed, have a monitoring system installed, or be permanently sealed with grout. The FLUTe™ liner is the only practical method now available to quickly but temporarily seal a hole. Initially FLUTe™ liners were installed in holes solely to seal the hole against cross-contamination; however two other advantages have since been developed; measurement of borehole hydraulic conductivity (K) and transmissivity (T) as the liner is installed (Keller et al., 2011) and high resolution temperature measurement in the static water column inside the liner (Pehme et al., 2010) as described below.

High Resolution Temperature Logging

High resolution temperature profiles measured in the static water column inside the borehole sealed with a FLUTe™ liner provide identifications of fractures with flow under ambient groundwater conditions. In traditional logging in unlined boreholes, cross-connection effects cause the temperature results in the unlined hole to misrepresent the ambient groundwater system (Figure 4). In this approach, once disturbance of the groundwater system caused by drilling and the open hole flow dissipates, which usually takes a few days, the temperature profile in the water-filled, lined hole shows many frac-

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tures with active groundwater flow without influence of the borehole (i.e. ambient conditions) as shown in Figure 4 comparing results from temperature logging in the same borehole under open and lined conditions (from Pehme et al., 2010). In hydraulically active fractures intersecting the borehole, groundwater flows around the liner and imparts its temperature to the static water column inside the liner as measured by an advanced temperature probe which resolves to better than 0.001°C. Typically temperature profiles in lined holes under ambient conditions show the perturbation deep into the rock of transient temperature variations imposed at ground surface from the atmosphere or subsurface urban infrastructure. The temperature profiles show the disequilibrium of the thermal regime caused by groundwater heat transport. Typically, temperature profiling in lined holes identifies many more hydraulically active fractures than in holes without a liner (Pehme et al., 2010). The use of temperature profiling for identification of hydraulically active fractures has been enhanced by the Active Line Source (ALS) technique (Pehme et al., 2007; 2012) in which the entire static water column inside the liner is heated and then the heat dissipation monitored by repeated profiling over several hours. This substantially increases the sensitivity and depth range for fracture identification. An ALS temperature profile taken at a dolostone site in 2010 is included as part of the composite dataset shown in Figure 5.

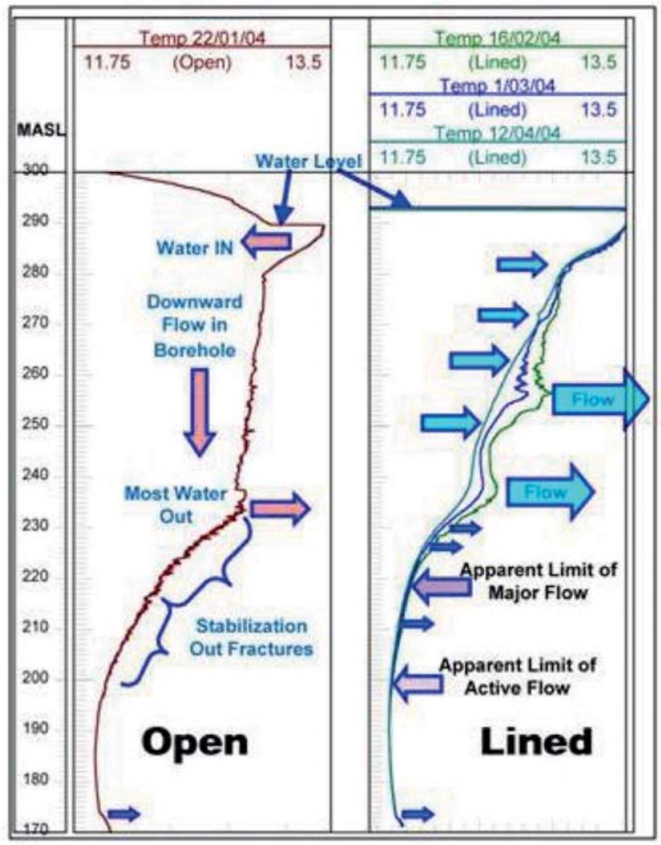

Fig. 4: *Comparison of interpretations of temperature logs collected in open and lined borehole at the Cambridge site (Table 1); blue arrows indicate major and minor flow zones (from Pehme et al. 2010). In the open hole, downward flow originating from shallow fracture(s) near the water table dominates the upper part of the temperature profile, and this vertical cross-connected flow masks flow zones identified in the lined hole representing ambient conditions. This shows how logging in open holes produces a misleading interpretation of natural flow conditions. The lined-hole temperature logs show many more flow zones and also a very different interpretation of the relative amounts of water movement in the zones that are identified or in some cases masked by vertical flow in the open hole.*

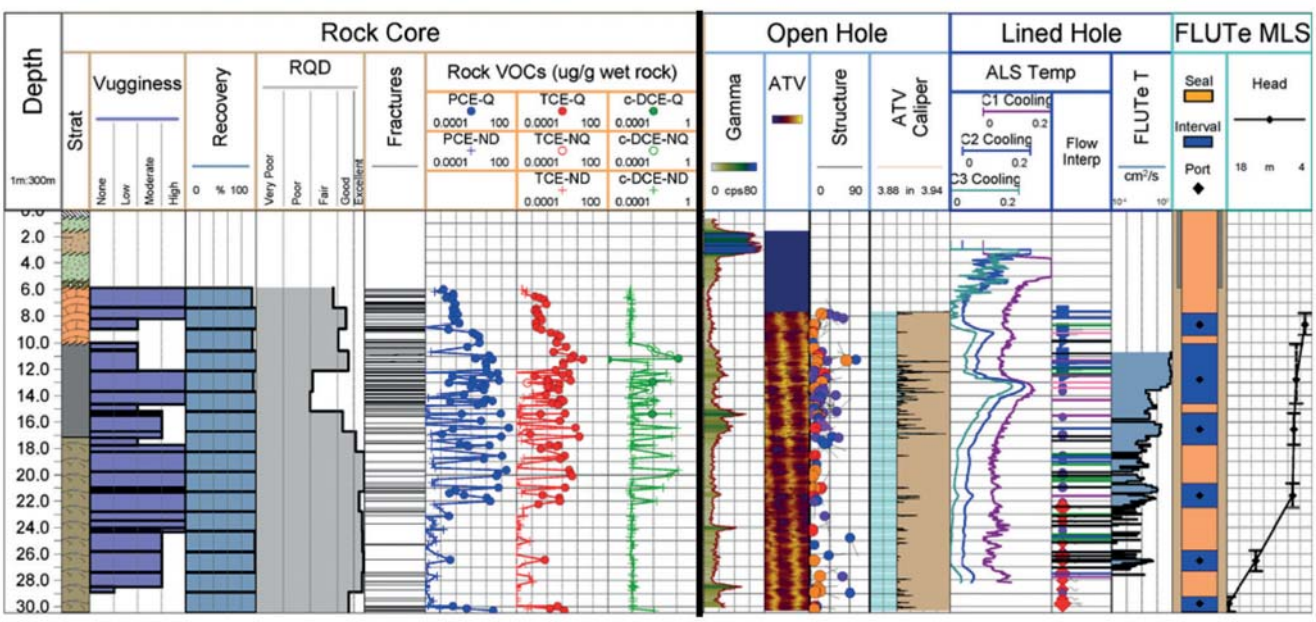

Fig. 5: *Example prepared using WellCAD of a portion of a composite DFN data set from rock core and borehole measurements and a MLS at a contaminated dolostone site in Guelph, Ontario (Table 1).*

Improved Hydraulic Tests Using Straddle Packers

Determination of the hydraulic nature of the borehole described primarily by the bulk transmissivity (T) of the entire borehole and depth-discrete transmissivity (T) along the length of the borehole are important components of DFN investigations. In the conventional approach for investigation of fractured rock, where groundwater flow rather than contaminant transport is the emphasis, packer tests carried out by the drillers in a few intervals in the hole are typically used to obtain 'order-of-magnitude' values for the transmissivity of the test interval. In research investigations the packer tests were sometimes done using a single test method along the entire borehole length using a fixed test interval such as one meter. However, in the DFN approach, where the focus is on determination of the hydraulic apertures, the goal is to obtain the most accurate values possible within the constraints of reasonable effort and cost. Hydraulic conductivity (K) or transmissivity (T) profiles along the holes are used to calculate Cubic Law based hydraulic apertures (2b), needed as inputs to DFN models. Depth discrete T values are derived from multiple hydraulic tests and aperture values are determined using the cubic law in which the hydraulic aperture is proportional to [T/N], where N is the number of permeable fractures in a test interval. In the DFN Approach, two types of hydraulic tests are used to obtain T profiles: (i) hydraulic tests using straddle packers set with small test intervals (~1-2 m), and (ii) FLUTe liner profiling. These two types of tests are used synergistically; liner profiling provides depth discrete T values for the entire length of borehole, and comprehensive packer testing is used to refine or confirm these T values for representative and/or anomalous intervals. The intervals of the borehole designated as a priority for packer testing are identified by core inspection, borehole logs and FLUTe™ profiling results. While hydraulic tests in boreholes using packers have existed for a long time, the DFN Approach uses advanced equipment and procedures for improved accuracy and precision because groundwater velocity is very sensitive to aperture and apertures and flow conditions are sensitive to induced stresses (Quinn et al, 2011a; 2011b). Quinn et al. (2012) describes packer testing equipment and approaches in more detail. In these tests, rubber packers with sleeves are used for improved seals to isolate an interval of the borehole and a suite of hydraulic tests are conducted including constant head step tests, rising and falling head slug tests, pumping tests and recovery tests to ensure tests conducted within the linear flow range. This comprehensive suite of hydraulic tests is conducted to obtain the best possible T values for calculating hydraulic apertures for velocity estimates with minimum error and uncertainty. To obtain hydraulic apertures using the cubic law, an estimate of the number of permeable fractures present in each test interval is required. There is typically more than one fracture present in each test interval, and all fractures are assumed to be the same size. Therefore, the calculated aperture is an average value for all of the fractures in the test interval. A range of fractures present in each test interval is first determined from all available data. (e.g. image, core and temperature logs). However, it is unlikely that all of the fractures identified by these methods are hydraulically active. A method has been developed to use the onset of non-Darcian flow in constant head step tests to aid in the selection of the number of hydraulically active fractures in each test interval (Quinn et. al., 2011b). This procedure results in a statistical spatial representation of the properties of the fracture network, which are then used in static and later in dynamic DFN modeling.

Conventional Borehole Geophysics

Conventional borehole geophysics also plays a role in the DFN approach. The geophysical logs that are considered to be most important are gamma, electrical resistivity and EM conductivity, which provide insights concerning the geology at the hole, and digital image logs, either acoustic or optical televiewer or at some sites both are used. The image logs are used primarily to identify fractures and their orientation and obtain a virtual caliper measurement (from the acoustic image log) which is used in the packer test planning and for assessing fracture frequency along with other lines of evidence. The above mentioned borehole geophysical methods all obtain information about the formation rather than about the nature of the water column in the hole. Conventional borehole geophysical methods such as fluid resistivity, flow metering and standard temperature logging are used only occasionally in the DFN approach because their value is minimal relative to the new borehole data acquisition methods such as high resolution temperature profiling inside lined holes. Also, these conventional geophysical methods are done in open holes and one of the objectives in the DFN approach is to minimize the time that the hole is open allowing hydraulic cross contamination. In the preferred scenario, the open hole geophysical logging is done immediately after drilling of the hole or most commonly at a later time when the liner is removed for a short period of time specifically to allow for the geophysical logging and in some cases the straddle packer hydraulic tests are conducted during this brief open-hole time interval. Some conventional geophysical logging can be done without diminished resolution inside the lined hole (e.g. gamma, neutron and apparent conductivity). Data from these conventional approaches are also combined with measurements made in the DFN approach such as physical property measurements for characterization of formation properties (e.g. porosity and bulk density). These conventional geophysical techniques can also be useful within the DFN approach for improving interpolations between boreholes and extrapolating away from the detailed investigation locations for plume scale and regional site conceptual model development that involves the static and dynamic modeling described below. The DFN coreholes serve as 'keys' that can be used to interpret the standard geophysical logs run in many regional and site holes. Without DFN coreholes serving as 'keys' the regional holes would be difficult or impossible to incorporate into the models.

Other Data Acquisition Methods in Open Holes

In the DFN Approach, there is emphasis on minimizing the time that the hole drilled for site characterization is allowed to be open because of the desire to minimize cross contamination effects. Sterling et al. (2005) describe an example of an open hole study of TCE cross contamination in fractured sandstone, showing strong effects even after only a short cross-connection period of a few days. However, a common circumstance at contaminated industrial sites is the presence of old monitoring wells with long open hole intervals, that have existed for many years or even decades. Commonly, these open intervals are between 5 and 20 or more meters in length and often not placed with knowledge of contaminant or hydrologic unit boundaries. Given that in sedimentary rock hydraulically active fractures typically occur at spacing of tens of cm or less, open hole intervals of only several to a few tens of meters may be cause for concern pertaining to vertical cross contamination between fractures and distinct hydrologic or contaminant zones. Therefore, there is need to assess the effects of such cross contamination by examining the conditions of vertical flow and hydrochemistry in the hole.

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This is most efficiently done by using a combination of several types of borehole measurements, most importantly borehole flow metering (heat pulse, EM or spinner) with and without pumping (e.g. Paillet, 2000) high resolution temperature profiling (Pehme et al., 2010) and passive water sampling (no pumps) at several depths. This type of sampling can be done using the Snap Sampler (Britt et al., 2010) diffusion sampler or a canister sampler. Although it is undesirable to allow open holes in contaminated areas to remain open longer than is essential for collecting critical data, there is usually the possibility in contaminated site investigations to conduct open hole studies at locations close to but beyond the contamination. We have found this detailed work in ‹clean› holes to be useful at some sites, particularly for conducting open hole geophysical logging and straddle packer testing to a degree much beyond what is recommended in contaminated areas.

Multilevel Monitoring Systems

The DFN Approach uses depth-discrete multilevel systems (MLS), sometimes along with conventional monitoring wells, to obtain hydraulic head and hydrochemistry profiles. A MLS is an assemblage of pipe/tubes/seals that creates discrete monitoring intervals across specific lengths of the borehole. Seals isolate each monitoring interval to provide depth-discrete hydraulic and hydrochemistry information representative of the specific interval in space and time. Because nearly all flow occurs in the fractures relative to the rock matrix, the data from the MLSs are considered to represent conditions in the fractures only. Specifically, MLSs are designed to collect temporal information on hydraulic head and water chemistry, both natural and contaminant. Because the water sampled by MLSs is drawn primarily from the fractures, the profiles of water chemistry obtained are different from, but complementary to, those obtained from rock core analyses. Four different types of MLSs are available from commercial suppliers: Water FLUTe™ from Flexible Liner Underground Technologies, the Waterloo and CMT® Systems from Solinst® Canada Ltd., and the Westbay® system from Schlumberger Canada Ltd. Each system offers a variety of design and equipment options. Choosing a MLS depends on site specific hydrogeologic conditions and monitoring objectives, with clarity for the selection provided by the complementary DFN Approach data sets. Once the type is chosen, the MLS is custom designed for each hole by specifying the lengths and positions of monitoring intervals and sealed segments based on data sets collected as part of the DFN Approach. Commercially-available MLSs can accommodate from 6 to approximately 40 monitoring intervals in a 150 m deep, 10-cm diameter borehole. In conventional practice, MLSs are typically designed with only a few monitoring intervals compared to the maximum number possible for each type of system. In the context of the DFN Approach, MLSs are designed to maximize the number of monitoring intervals to provide the most detailed data possible and to avoid cross-connection of different aquifer and aquitard units. This desire for many monitoring intervals is based on experience showing that the critical intervals where detailed head profiles are needed cannot in general be predicted in advance (e.g. Meyer et al., 2008; 2012). For the MLS to provide hydrochemistry representative of in situ conditions, sufficient time must pass after installation to allow cross-contamination effects to dissipate, which may take many months or even years. MLSs are used as part of the characterization phase of contaminated site studies, but can also be used for long-term groundwater monitoring. Depending on which of these two phases is the focus, a different type of MLS may be used.

Data Storage and Management

The DFN Approach generates highly resolved spatial and temporal data from multiple sources requiring a data management system with exceptionally large data storage capacity and the capability to explore relationships between the various datasets to produce integrated interpretations. Existing software for data storage and management were found to be inadequate; therefore, a relational database system was developed specifically for datasets collected using the DFN Approach. This database system improves efficiency and consistency in data collection, facilitates QA/QC procedures during all stages of data acquisition and management, and assists in data interpretation. Furthermore, this database system ensures the DFN data is comprehensively archived, which is critical given the volume of the data collected, effort and expense in collecting the various datasets, and the time required to fully capitalize on the data from a scientific standpoint given the long-term nature of these sites and problems. Use of the database system starts in the field at the drill site to ensure the coring data being collected are consistent and of the highest possible quality. The core is photographed, described and sampled following a framework designed to capture all data required by the DFN Approach, expose errors and omissions, force consistency between logging personnel and minimize bias. User input and experience is used to continually update and streamline the database system. The data base system easily interfaces with or outputs data for use in data display and static modeling (described later) software such as WellCAD, Viewlog and Petrel. The focus on data storage and management within the DFN approach is due, in part, to the recognition that large numerical models of groundwater flow and contaminant transport are prone to diminished credibility if the modeling process is not traceable and transparent. The terms traceable and transparent imply qualified persons external to, and independent of, the project are able to retrieve all site data used to construct the model, inform important decisions, and assess assumptions in a convenient manner. Ultimately, if desired, such persons should be able to run the models to assess conclusions based on model outputs. This level of transparency and traceability is not possible without a comprehensive data management system.

Example DFN Field Datase

The DFN Approach was applied in Fall 2010 to six boreholes in Silurian Dolostone at a site in Guelph, Ontario contaminated with PCE, TCE, and their daughter products. Figure 5 shows a comprehensive DFN data set collected at one location from this site. The left panel focuses on data collected from the continuous rock core including geologic data sets (stratigraphy, vugginess, fractures) and rock core contaminant profiles. The very closely spaced rock core contaminant analyses show nearly all of the mass is between 10 and 22 mbgs and the mass is not limited to or consistently distributed within a distinct stratigraphic unit. There was no reason to suspect this contaminant distribution from the general hydrogeological circumstances, and therefore, close sample spacing along the entire core was essential. The right panel shows data sets collected from the corehole. Data collected both from the core and the corehole provide multiple lines of evidence for a dense fracture network. Fractures identified from the continuous core and acoustic televiewer show many fractures but cannot differentiate between fractures with active groundwater flow and those without. The datasets collected from the FLUTe lined hole include active line source (ALS) temperature logging and a FLUTe transmissivity profile. These datasets are directed at identifying transmissive fractures and fractures with active groundwater flow and indicate the presence of many active fractures. All of the DFN datasets were used to design a MLS targeting zones of flow/high contaminant concentrations without cross-connecting different hydrogeologic units. The MLS is used to collect head profiles and provide groundwater samples for a wide range of hydrogeochemical and contaminant analyses. The head profile shows three distinct segments: a small change in head with depth in the upper portion, a flat section of minimal vertical gradient in the middle portion, and a large change in head with depth in the lower portion of the hole. The flat portion of the head profile suggests a dominance of horizontal flow and a dense network of interconnected fractures. The sharp change in head with depth is likely indicative of an aquitard unit. An additional five coreholes were completed, four to 30 m and one to 72 m depth extending into the shale aquitard, with comprehensive data sets obtained at each. These six coreholes provide the basis for a detailed SCM and decisions about future investigations.

Modeling

Two general types of modeling are conducted as part of the DFN approach: (1) static and (2) dynamic modeling. Emphasis on static modeling (i.e. 3-D spatial) to represent geology and assist in delineation of hydrogeologic units and nature and extent of contaminants as examples is an important step prior to dynamic flow and transport modeling. In the preferred approach to static and dynamic modeling, these modeling efforts are begun early in the site investigation process so that the models are tools 'to organize thinking' and 'to guide data collection (Bredehoeft, 2010). Each type of modeling is described in more detail below.

Static Modeling

The main objectives of static modeling is to interpolate and extrapolate the information between boreholes so that the models for groundwater flow and transport are based on the best possible three dimensional representations of the geology, physical hydrogeology and contaminant distributions. Static modeling is aimed at formalizing the development of these spatial distributions using advanced software referred to as static models. The initial step in static modeling is comprehensive interpretation of all of the various types of data sets on a hole by hole basis. The foundation for use of DFN data in static models is the compilation, QA/QC, storage, and management of borehole data in the relational database system. The data management system is essential to the appropriate and efficient display of DFN data. For this one-dimensional step, various software are used, culminating in the use of WellCAD for data integration and display (e.g. Figure 5). For the extension of the interpretations into three dimensional space, Petrel or similar software becomes the primary tool. At the rudimentary level, these extensions are based primarily on basic statistical considerations; however, ultimately there is need to make more formal use of geologic origins of the geologic units and geomechanical considerations for the fracture networks. In conventional approaches for groundwater flow and transport modeling, the step between assembling the borehole data, borehole by borehole, is typically informal based on simple algorithms and personal judgment. An objective in the DFN approach is to expand and formalize this step to take advantage of methods developed primarily in the petroleum industry and to better inform or translate these methods to shallower, freshwater systems.

Dynamic Modeling

Dynamic numerical models advanced to simulate flow and transport in the 1990s included complexity of fracture networks and processes for interactions between fractures and matrix. However, computing power was quite restrictive and, most importantly, no sufficiently detailed field studies of existing contaminant plumes were available to parameterize or ground truth these models. The purpose of applying the DFN Approach for field site characterization is to develop reliable site conceptual models (SCMs) and related mathematical models to serve as the framework for decisions concerning long term monitoring, remediation, and site management. Dynamic models for groundwater flow and contaminant transport are used to represent the present state of contaminant distributions, make future predictions of transport and fate, and evaluate remediation alternatives and efficacy. However, models for flow and transport are only as good as the SCMs on which they are based; therefore, the development of the SCM is the most important step in the overall modeling process requiring integration of conceptual models for geology, hydrogeology, and hydrogeochemistry. The ultimate goal of mathematical modeling is simulation of contaminant transport and fate. This modeling must be done using DFN transport models in which processes in both the fractures (advection and dispersion) and the rock matrix blocks between fractures (diffusion, sorption, and reactions) are adequately represented. Although 3-D numerical DFN models for contaminant transport exist (e.g. HydroGeoSphere, FEFLOW), none has shown to be capable of representing fractured rock domains large enough to encompass actual plumes at the field scale. Therefore, a practical approach at present is to apply 2-D DFN transport models (e.g. FRACTRAN) to represent plume evolution and predict future plume behavior with hydraulic boundary conditions and groundwater flux constrained with calibrated 3-D EPM groundwater flow models (e.g. Chapman and Parker, 2011). Output from DFN simulations can be compared stylistically with field data collected using the DFN Approach, such as rock core VOC profiles and head and concentration data from MLS. The 2-D DFN models are recognized as simplifications of reality because they are 2-D and the statistical generation of fracture networks cannot capture the full complexity and heterogeneity of actual fracture networks and thus deterministic simulations are not a goal. However, when sufficient characterization data have been collected to define reasonable input parameters, DFN simulations can provide valuable insights into controls on contaminant attenuation caused by diffusion and other processes. Thus a goal is apply DFN models which incorporate relevant processes and their interplay in both the fractures and matrix for stylistic representation of field conditions, and also adequately represent plume attenuation caused by diffusion and other processes.

Figure 6 shows results of 2-D DFN simulations tailored to an intensively studied plume at the California site. Darcy flux along the plume flowpath was obtained from a 3-D FEFLOW model constructed for the site. The mean matrix porosity of the sandstone at this site is about 13%. The dense fracture network (Figure 6a) has lognormal fracture apertures with mean of 100 microns and variable lengths (Figure 6b). The average linear groundwater velocity in the fracture network can be estimated using: , where K_b is the bulk hydraulic conductivity (derived from the flow simulation), i is the average hydraulic gradient and f_f is bulk fracture porosity (provided as model output based on the generated fracture network), which assumes all flow occurs through the interconnected fracture network. With imposed hydraulic gradients of 1% horizontal and 0.5% verti-

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cal (downward), the average linear groundwater velocity is about 7 m/day for this scenario. Simulated groundwater velocities in some fractures are much higher than this average value with a maximum of about 30 m/day (Figure 6c), indicating potential for rapid plume migration in the absence of diffusion and other processes. Simulation results show rates of plume migration are much slower even without degradation (Figure 6d, LHS), with the plume front less than 800 m downgradient after 50 years, and peak concentrations are significantly attenuated with distance. Incorporation of even very slow rates of contaminant degradation can have a substantial impact on plume attenuation (Figure 6d, RHS). Such low degradation rates, whether via biotic or abiotic processes, are too low to be measured in laboratory studies over practical time periods. Rates of degradation in the rock matrix of significance in fractured rock settings are much slower than typical rates reported for microcosm and field studies in unconsolidated sediments for chlorinated solvents (e.g. Wiedemeier et al., 1999). Degradation in the matrix, besides causing direct contaminant loss, also has the effect of enhancing diffusion since higher concentration gradients are maintained driving diffusion into the matrix.

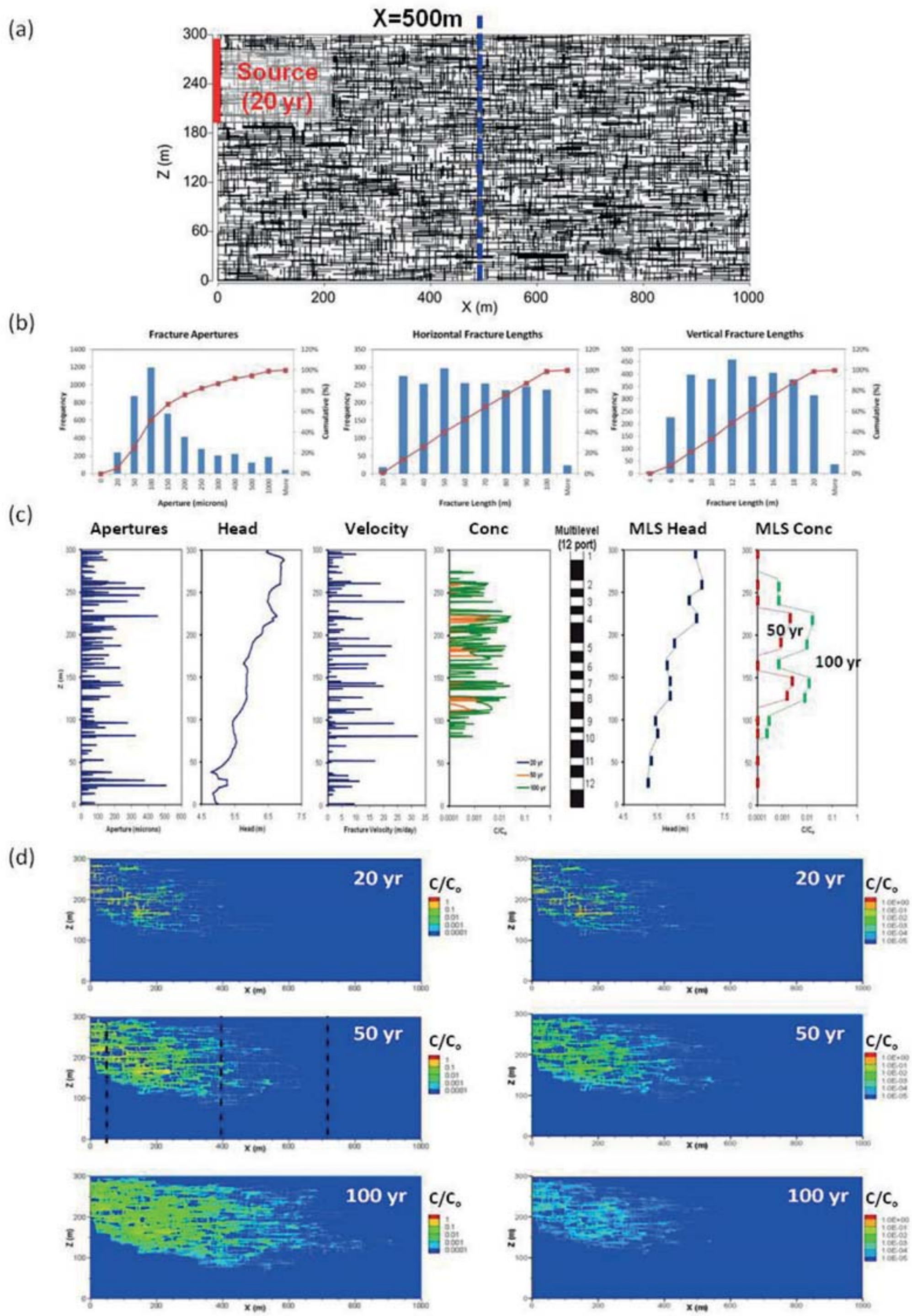

Fig. 6: *Example FRACTRAN DFN simulation tailored to California site: (a) fracture network, (b) aperture and length distributions, (c) profiles showing fracture apertures and simulated head, fracture flow velocities and concentrations at x=500 m and head and concentrations for a hypothetical MLS, and (d) simulated TCE plume at 20, 50, and 100 years for scenarios with no degradation (LHS) and with slow degradation (10-yr half-life).*

Figure 7 shows a comparison of simulated versus field conditions for a plume at the California site. The plume was delineated using two transects and a longsect along the plume flowpath (Figure 7b). The depth-discrete rock core total equivalent TCE porewater concentrations along the plume longsect were depth-averaged over 6 m intervals to represent bulk scale plume conditions. Simulation results are from the scenario shown in Figure 6 without degradation, with results taken at 60 years, which is consistent with elapsed time between when initial releases occurred at the site and the field data were collected. The FRACTRAN DFN simulation results reasonably represent maximum and depth-averaged field concentrations along the longsect (Figure 7c). Also the bulk plume characteristics (Figure 7d) are also reasonably represented by the model (Figure 7e). This provides good confidence that this approach, combining 2-D DFN models for contaminant transport with flow constraints from 3-D EPM flow simulations, using site specific parameters, can produce simulated plume conditions that show excellent representation of plume style and contaminant distributions and the magnitude of plume attenuation. DFN simulations can also be used for exploring remediation efficacy (e.g. Parker et al., 2010). Similar application and comparisons with field data is underway at several of the detailed study sites.

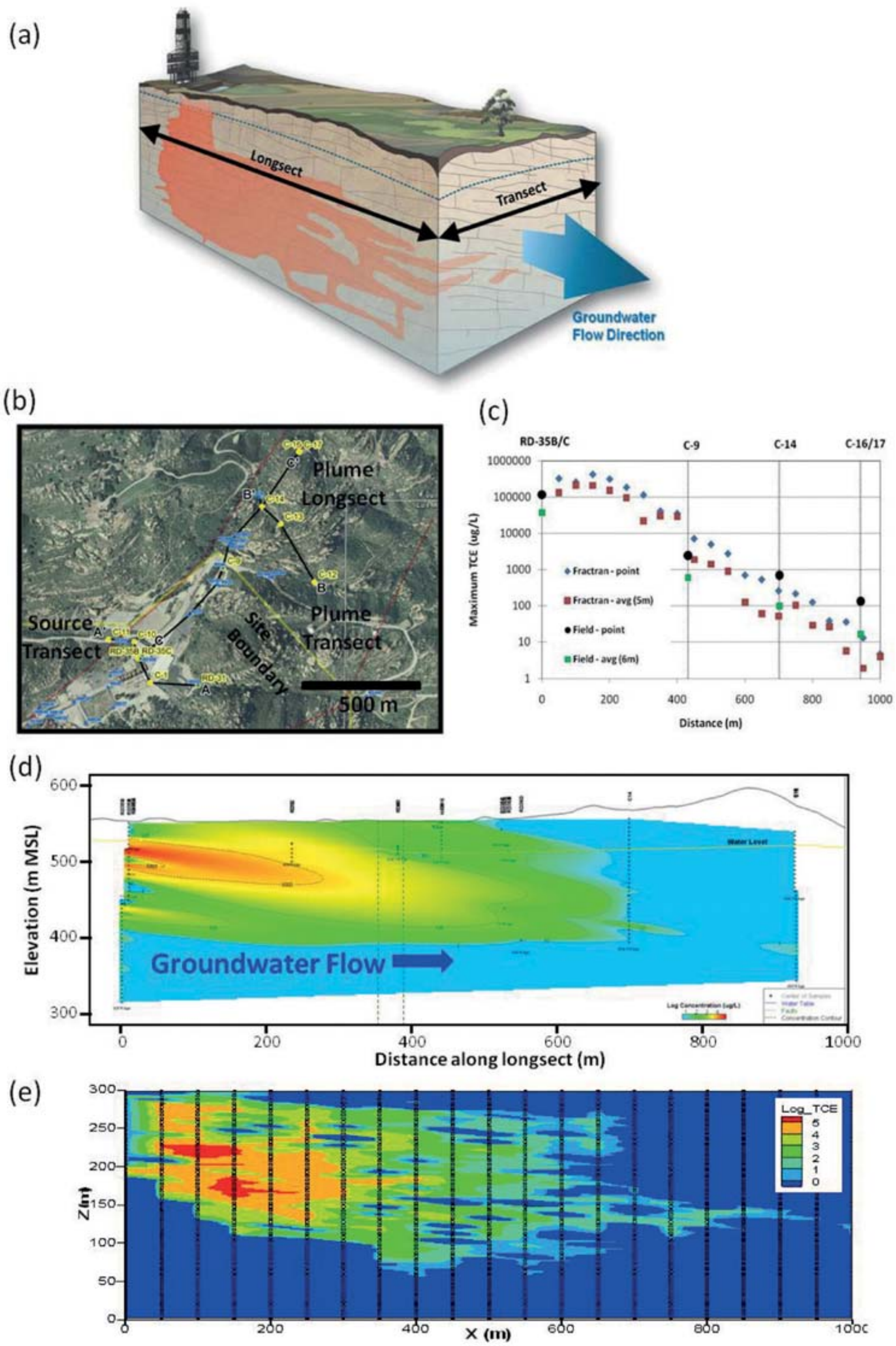

Fig. 7: *Longsect comparison between FRACTRAN 2-D DFN simulation tailored to a plume at the California site and field delineated plume via rock core sampling: (a) schematic and use of transects and longsect, (b) plan map of field site with plume delineated along two transects (source area A-A' and plume area B-B') and along a longsect C-C', (c) comparison of field versus simulated maximum equivalent TCE versus distance along longsect, and comparison of (d) field versus (e) simulated depth averaged TCE along longsect.*

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Summary of Key Findings

The application of the DFN approach at the eight intensive study sites (Table 1) has resulted in several general conclusions concerning fracture networks, contaminant distributions and transport and fate processes common to all of the sites. The contaminant distributions at these sites developed over decades essentially represent long term natural gradient tracer experiments. The details of the rock core profiles provide insight regarding fracture spacing in which transport occurs. Prior to the initiation of these contaminated site studies using the DFN approach, there was concern that complexities in the geologic structures and fracture network characteristics would cause the subsurface source zones and plumes to be extremely difficult or practically impossible to locate and delineate. However this has not turned out to be the case for any of the eight sites. The fractures in which active groundwater flow occurs are numerous, generally closely spaced and well connected, which has resulted in the contaminant plumes being orderly and monitorable, rather than being chaotic or disorderly and not amenable to reliable monitoring (Figure 8). The characterizable behavior of contaminants at these sites is attributed to the strong interplay between the matrix and fractures due to dense, interconnected fracture networks.

Hydraulic apertures are typically in the range of 50-500 microns and the average linear groundwater velocity (Darcy flux divided by the bulk effective fracture porosity) is generally a few to tens of meters per day. While average linear groundwater velocities in fractured sedimentary rock are relatively large, matrix diffusion has caused the contaminant plumes at the eight sites to be very small relative to expectations based on such velocities. This strong plume-front retardation in fractured sedimentary rock is primarily a result of matrix diffusion causing contaminant transfer from groundwater in fractures to the low permeability rock matrix, as well as contaminant storage in the matrix due to sorption. Matrix diffusion has such a strong influence on plume behavior because in this ground-truthed SCM contaminant transport occurs in a well-interconnected fracture network with closely spaced fractures where there is large surface area for diffusive mass transfer.

At seven of the eight sites, the initial DNAPL mass has mostly or entirely transformed into dissolved and sorbed mass in the rock matrix. Thus, there is no difference in the state (phase and distribution) of the contaminant mass between the former DNAPL source zones and the plumes, consistent with expectations for DNAPL disappearance by dissolution and diffusion (Parker et al., 1994; 1997). At such "aged" sites contaminants continue to diffuse into the matrix blocks in some zones while outward diffusion back into the fractures occurs in other zones. Such slow back diffusion causes contaminants to persist in former DNAPL source zones for extended periods (decades to centuries or longer) despite complete dissolution of the original DNAPL phase. The implication to remediation of contaminant mass residing primarily in the matrix is that the return of groundwater to drinking water standards requires removal of essentially all of the matrix mass (Parker et al., 2010). However the evolution of the source zone to a non-DNAPL condition causes reduced contaminant mass loading over time, which results in maximum concentrations in the plumes also diminishing over time. Microbial degradation products of chlorinated solvents have been found at most of the

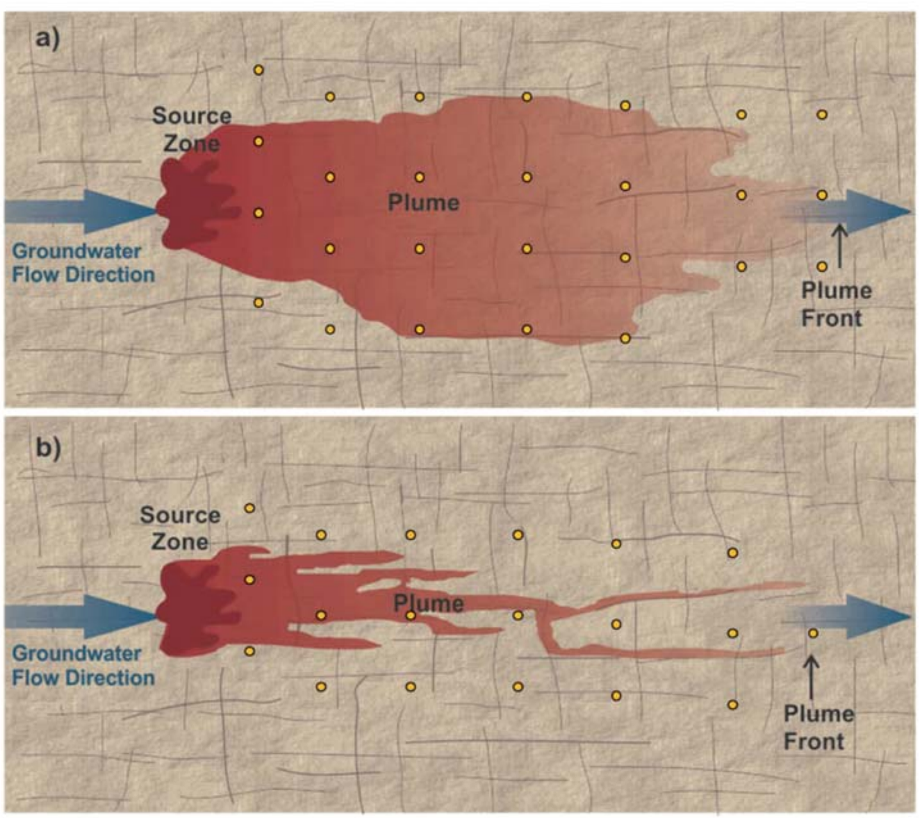

Fig. 8: *Two conceptual plumes caused by DNAPL entry into fractured rock: (a) monitorable plume due to strong transverse dispersion and spreading in well interconnected fracture network, and (b) alternative model with plume funneling into a small number of major fractures making monitoring difficult.*

sites, indicating that parent chemicals have undergone some degree of mass reduction due to degradation, with evidence that much of this degradation occurs in the rock matrix. Strong transverse spreading in the fracture networks and, in some cases, degradation has contributed to plume attenuation that has produced nearly stationary plumes in these sedimentary rock sites. The many methods utilized by the DFN Approach to establish fracture occurrence and frequency provide substantial confidence in conclusions concerning the occurrence of ubiquitous, well connected fractures that give rise to the orderly, monitorable, nearly stationary plumes observed at the eight intensively studied sites due to the combination of processes operating in the fractures and the matrix.

Directions of Current Research

Although the DFN Approach for investigating contaminated sites on sedimentary rock has now reached a stage sufficiently advanced for comprehensive application at many sites, several elements are the focus of collaborative research aimed at improvements; some of the topics of the current research are indicated here. Confidence in the understanding of the fracture network characteristics can be strengthened through assessment of distribution and transport of other components of the system, and therefore effort is directed at investigations of natural isotopes such as atmospheric tritium as natural tracers and at simulations of heat transport to better understand the ambient temperature distributions. High resolution temperature profiling methods inside lined holes are being extended, aimed at determining groundwater flux, velocity and flow direction. Tools are being developed independent of temperature to identify individual fractures with active groundwater flow and to measure the fluxes of groundwater and contaminants in these individual fractures. In collaboration with the companies that manufacture MLSs, design modifications are being explored and tested to improve effectiveness and versatility. At some bedrock sites, the contaminant plumes extend towards locations such as hill slopes, rivers or estuaries where access by standard rock drilling rigs is too expensive, difficult or impossible without causing excessive terrain or ecological damage. Therefore monitoring systems are being developed to install in small diameter (<8 cm or 3 inches) holes drilled using small portable machines widely used in remote terrain by the mineral exploration industry. The field components of the DFN approach are primarily suited for application in holes that are between four and seven inches in diameter. The four inch minimum diameter cores come from the common practice of drilling PQ and HQ sized core holes. In the mining industry, NQ size holes (nominal 3 inch diameter) are most common and therefore to extend the application range of the DFN approach, adaptations are in progress for 3 inch holes. Another reason to adapt the DFN approach for 3 inch holes is to extend the reach of the approach to locations that cannot be accessed by conventional PQ and HQ coring drill rigs, which are typically truck or track mounted and require a large space not suitable for all drill site conditions (e.g. steep slopes and remote areas). For this extended application of the DFN approach, some of the downhole tools and multilevel devices need to be redesigned or adapted. Field trials for several different types of these portable drilling machines are underway.

The use of static models such as Petrel and Fracman is in the early stage for integrating all forms of site data, interpolating between investigation locations and developing comprehensive interpretations. Although there are many different software packages available for manipulating, displaying and modeling site data, the diversity of the DFN data sets and the immense size of these sets have proven to be an obstacle to efficient comprehensive interpretations. Therefore, better interfaces are needed between the software packages. Concerning borehole geophysics, there is a need to know more about the resolution obtainable from various tools when used inside FLUTe lined holes. Advanced borehole geophysical methods developed in the petroleum industry for improved identification of fractures, fracture and rock matrix properties are being assessed.

Acknowledgment: The DFN approach includes a diverse study of field and laboratory methods, field studies at many field sites, and the application of several advanced numerical models. This development of the methods and the applications has relied on strong collaborations and assistance from many individuals and organizations too numerous to acknowledge all here. Essential collaborations with faculty members include: Tadeusz Gorecki (Univ. Waterloo) on development of advanced rock core VOC analysis, Ramon Aravena (Univ. Waterloo) on geochemistry and isotope analyses, John Molson (Univ. Laval) for advancing application of numerical models for heat transport and John Greenhouse (Retired, Univ. Waterloo) for ideas concerning borehole geophysical methods. Peeter Pehme and Pat Quinn, through PhD thesis research at the University of Waterloo and more recently their work at the University of Guelph advanced the innovations in temperature profiling and packer testing methods, respectively. Jessica Meyer and Jonathan Kennel were the primary developers of the relational data storage and management system. Maria Gorecka provided analytical laboratory support. The DFN Approach has advanced through the efforts at field sites of several former students including: Diane Austin, Leanne Burns, Jennifer Hurley, James Plett, Sean Sterling, Chris Turner, Jonathan Kennel and Amanda Pierce, and present students including Jessica Meyer, Thomas Coleman, Jonathan Munn and Kenley Bairos and contributions by former post-doctoral fellows Jerome Perrin and Glaucia Lima. Frank Barone of Golder Associates supervised physical property measurements on core samples from several of the sites, including diffusion coefficients. Edward Sudicky and Rob McLaren (Univ. Waterloo) provided the Fractran code and support in its use. Paul Martin and Darron Abbey of AquaResource contributed to combining application of EPM flow and DFN transport models. The research program is funded by: the Natural Sciences and Engineering Research Council of Canada (NSERC) through an Industrial Research Chair held by Beth Parker, the Canadian Foundation for Innovations (CFI) and University Consortium for Field-Focused Groundwater Contamination Research. Major contributions from site owners have been essential. Collaborations with and technical assistance from groundwater technology companies, most notably Westbay Instruments (Schlumberger) and Flexible Liner Underground Technologies (FLUTe), and support from companies, including R.J. Burnside & Assoc., AquaResource Inc., Sanborn Head and Assoc., Dillon Consulting, Geosyntec, MWH, the City of Guelph, the Regional Municipality of Waterloo and Schlumberger Canada are appreciated. Stone Environmental Inc. provided support for rock core sampling and analysis at some of the study sites, and are set up to provide this service commercially, referred to as the CORE DFN™ Approach. An earlier version of this paper was presented at the 2011 NGWA Focus Conference on Fractured Rock and Eastern Groundwater Regional Issues on September 26-27, 2011, Burlington, Vermont.

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Attachment 2.

Carl Keller, John Cherry and Beth Parker. New method for Continuous Transmissivity Profiling in Fractured Rock. Ground Water 2013

Groundwater

New Method for Continuous Transmissivity Profiling in Fractured Rock

by Carl E. Keller[1], John A. Cherry[2], and Beth L. Parker[3]

Abstract

A new method is presented to search for hydraulically transmissive features in open boreholes in bedrock. A flexible borehole liner made of a watertight, nylon fabric is filled with water to create a constant driving head to evert (reverse of invert) the liner down the hole so that the liner pushes the borehole water out into transmissive fractures or other permeable features. The descent rate is governed by the bulk transmissivity of the remaining permeable features below the liner. Initially, the liner descent rate or velocity is a measure of transmissivity (T) of the entire hole. As the everting liner passes and seals each permeable feature, changes in the liner velocity indicate the position of each feature and an estimate of T using the Thiem equation for steady radial flow. This method has been performed in boreholes with diameters ranging from 96 to 330 mm. Profiling commonly takes a few hours in holes 200- to 300-m long. After arrival of the liner at the bottom of the hole, the liner acts as a seal preventing borehole cross connection between transmissive features at different depths. Liner removal allows the hole to be used for other purposes. The T values determined using this method in a dolostone aquifer were found to be similar to the values from injection tests using conventional straddle packers. This method is not a replacement for straddle-packer hydraulic testing of specific zones where greater accuracy is desired; however, it is effective and efficient for scanning entire holes for transmissive features.

Introduction

Understanding the flow in fracture networks in bedrock is needed for assessments of contaminant transport and fate, groundwater resource management, groundwater control at mine sites, and other purposes. In most types of rock, groundwater flow occurs primarily in interconnected fractures where the rock matrix blocks between fractures have much lower permeability. For the purpose of contaminant transport assessment, Neuman (2005) draws attention to the importance of identifying all the fractures in each borehole potentially involved in groundwater flow, rather than just the few features that may appear to dominate flow. Parker et al. (2012) provide an overall framework and approach for acquisition of data for individual fractures and fracture networks, referred to as the discrete fracture network (DFN) approach with emphasis on the importance for contaminant transport in all the fractures in the network, and Parker et al. (2011) show the importance of DFN characteristics on contaminant transport and attenuation at a site situated on fractured sandstone. The method described in this article is a new option available for use in the search for hydraulically transmissive features in boreholes. This method is typically used in conjunction with other methods of borehole data acquisition including borehole geophysics, borehole imaging, and in some cases also used in conjunction with hydraulic tests using packers with focus on particular fractures.

The limitations of existing methods used in the search for permeable features in fractured rock boreholes are substantial. Borehole televiewing (optical, acoustic, or electrical) commonly shows many fractures in each borehole but does not discern the transmissive fractures from those that are closed or filled with cement and therefore not transmissive. In open boreholes, the water column commonly has vertical flow because of cross connection between transmissive fractures with different hydraulic heads in the formation (e.g., Price and Williams 1993; Sterling et al. 2005), and therefore fluid electrical resistivity or temperature measurements within the open-hole water column typically discern a few major features with flow but not the many intermediate and lesser features (Pehme et al. 2010, 2013). Conceptual fracture networks based only on a few major fractures present in each hole and excluding many other transmissive fractures are unrealistic and produce inaccurate contaminant plumes in transport simulations. Hydraulic tests involving water injection into, or withdrawal out

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of, permeable intervals isolated with inflated packers measure the transmissivity of these intervals. When such tests are done throughout the entire borehole length using short test intervals (e.g., 1 to 2 m), the locations and transmissivities of all substantial transmissive zones become known; however, testing an entire borehole using short test intervals typically takes several days, and therefore is rarely done except in research-intensive projects (e.g., Novakowski et al. 2006; West et al. 2006). Therefore, efficient methods capable of identifying and measuring the transmissivity of all or nearly all potential permeable fractures in each borehole are needed.

This article describes a method recently developed for conducting hydraulic tests in open boreholes in fractured rock. The purpose of this method, referred to here as transmissivity profiling, is to: (1) quickly identify along the entire length of open hole the permeable fractures or other permeable features; (2) estimate the transmissivity and also in some cases the hydraulic conductivity; and (3) determine the bulk transmissivity of the entire length of open hole. This method is also known more simply as liner profiling or the drop liner method. The method is suitable for use in holes in rock that have a casing sealed through the overburden and/or through the weathered zone into the intact rock. The open hole below the casing must have no obstructions or substantial restrictions. This method uses a tubular length of impermeable urethane-coated nylon fabric, closed at the bottom, which is very flexible so that it can be rolled onto a reel and positioned at the hole to begin the profiling procedure. The liner is about the same length and diameter as the borehole. The liner is slightly elastic and about 10% larger than the nominal borehole diameter so it can conform to the borehole wall. To initiate the profiling procedure, the liner is filled with water to inflate it and to create a hydraulic head differential between the inside and outside of the liner. This head differential causes the liner to descend down the hole acting as a piston. As this piston descends, water below is forced out of the hole and into the formation through transmissive features. The descent rate of the piston at each depth in the hole is a function of the transmissivity of the remaining length of open hole below the piston. Hence, with measurement of the descent rate and other factors, a transmissivity (T) profile is obtained from the top to the bottom of the hole. Changes in descent velocity of this piston along the hole indicate the presence of the transmissive features.

The impetus for the use of flexible liners to seal holes came from our recognition of the need to minimize cross contamination at sites on fractured rock with chlorinated solvent contamination, an example of which is described by Sterling et al. (2005). In such cross contamination, the borehole acts as a conduit to connect fractures with higher hydraulic head to fractures with lower head in the same hole. This induces vertical cross flow between fractures. These cross connections can worsen the degree of contamination at the site and confuse the hydrochemical conditions being investigated. Price and Williams (1993) describe a fractured rock hole where such cross connection changed the natural hydrochemistry of the formation. Pehme et al. (2010, 2013) used high-resolution temperature profiling in lined and unlined holes to show that cross connections are a common feature of holes in fractured rock and that open holes severely hinder the ability to characterize the natural system. Minimization of cross contamination because of vertical flow in holes drilled in contaminated site investigations on bedrock has become desirable in many jurisdictions. For example, it is required in the state of New Jersey that all annular space between well casings and annular space between casing and borehole be sealed within 24 hours (NJ Reg. 7:9D–2.2 (a) 10) and that "there shall be no more than 25 feet of total open borehole" (NJ Reg. 7:9D–2.4 (a) 4) (NJDEP 2012). The use of flexible liners to seal boreholes to temporarily prevent cross contamination was initiated in 2001 and since then many hundreds of holes have had flexible liners installed for this purpose.

The transmissivity profiling method introduced in this article was invented by the first author, as described in patents (C.E.K., US patent nos. 6910374 and 7281422 and foreign patents). The seals installed by this method are temporary because the intended use of the liner is to create a seal until such a time as the borehole is needed for geophysics, hydraulic testing, and/or installation of a monitoring well, after which the liner can be removed with relative ease. Profiling measurements are conducted during liner installation with the intent that the liner will seal the hole once the profiling procedure has been completed.

Although this article only reports results from a field study area in a dolostone aquifer, the method has been applied in more than 300 rock boreholes at more than 60 sites across North America and in Europe. The shallowest hole profiled so far is 18 m and the deepest is 450 m in a sandstone borehole in California. Borehole diameters have spanned the range from 96 mm (3.8 inches) to 330 mm (13 inches). The depth to standing water in the holes has ranged from artesian conditions to more than 100 m. In nearly all cases where this profiling method has been applied, the liner has been left as a seal in the holes for a period of several weeks to many months before using the holes for other purposes. Our general conclusions concerning applicability and limitations of the profiling method presented in this article are based on the broad experience from all of these boreholes tested in many types of fractured rock.

To demonstrate the nature of results from the liner measurements and interpretive issues, we present results from three core holes in a 100-m-thick fractured dolostone aquifer. This aquifer provides the water supply for the city of Guelph, Ontario, Canada. Results from this field area were selected because these holes have been used for many other types of data acquisition for fracture identification and hydraulic conductivity determinations, including core logging, borehole geophysics with acoustic televiewing, flow metering, high-resolution temperature profiling (Pehme et al. 2010, 2013), and hydraulic tests using straddle packers and pumping tests (Quinn et al. 2011a). The comprehensive data collected from these holes allow comparison of liner profiles to other indications of fracture presence and transmissivity. Overall, development of the liner profiling is still in the early stage of application in contaminated site investigations. This article introduces the method as well as initial results and considers hydrogeologic and other factors that influence the performance and limitations of the method.

Approach

The details of the liner design and parameter values for the profiling procedure are specific to each hole; however, the generalities, as described here, are common to nearly all holes. The liner fabric (the urethane-coated material) is selected to have the combination of strength and flexibility suitable for the borehole diameter and the site-specific hydrogeological conditions. An essential objective is to select a fabric that will not rupture but have good flexibility for the profiling and also the strength to accommodate the necessary applied head differential established on arrival of the bottom of the liner at the bottom of the hole where the liner function is to form a seal along the entire hole. Previous experience related to the site conditions guides the selection of the characteristics of the liner material for each hole. If the fabric is too stiff and inflexible, it will create too much friction while descending down the hole. If the fabric is too thin and extremely flexible, it is more prone to rupture. Rupture occurs when the head of the water column inside the liner excessively exceeds the head in the fractures outside the liner. We expect that profiling of holes with diameters as small as 75 mm or even 51 mm will become feasible in the future with the use of very thin, extremely flexible liners made of strong enough material. Each liner is custom made and shipped from the FLUTe Ltd. manufacturing facility in Santa Fe, New Mexico to the field site on a reel. The outer diameter of reel plus the liner ranges between 0.6 and 1.0 m.

The profiling procedure evolves in stages. First, as shown in Figure 1a, the reel loaded with the liner is positioned at the hole and the open end, which is the top of the liner, is pulled off the reel and attached with a clamp around the top of the steel casing that protrudes above-ground surface. This casing extends through the overburden or weathered rock downward into the intact, stable rock mass. After clamping of the liner top to the casing head, the liner is pushed by hand at an arm's length downward into the casing to form an annular pocket. The second stage begins when water is added, usually from a hose connected to a water tank, into this pocket to create weight that drives the liner down the casing into the open rock hole below, as shown in Figure 1b. The process by which the liner goes down the hole is known as eversion such that, as the liner descends, the fabric initially on the inside of the liner while it was on the reel becomes the outside of the liner pressing first against the casing and then deeper against the rock wall. However, while the liner is descending through the air-filled segment of casing

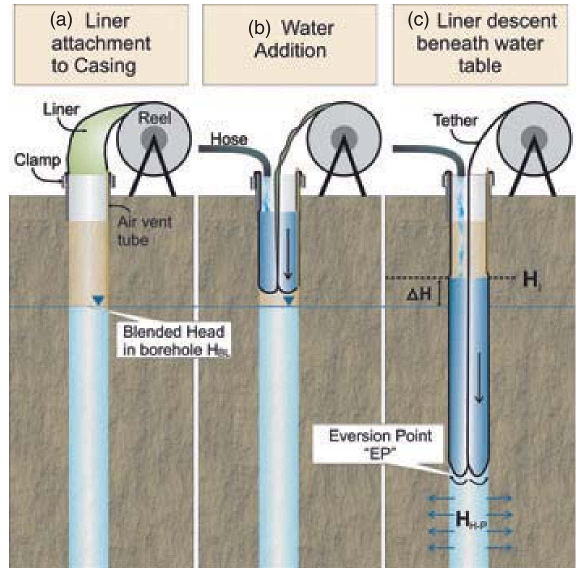

Figure 1. The stages in installation of blank FLUTe™ liner: (a) top of liner from the reel is clamped onto the top of borehole casing; (b) the liner is pushed by hand down into the casing so that water can then be added to cause the liner to descend by eversion; and (c) the liner descends below the static water level in the borehole and water is added to maintain a positive hydraulic head differential between the inside of the liner and the initial static water level, referred to as the blended head.

above the static water level, the air must be allowed to escape through a slotted tube extending to the water level.

Once the liner reaches the static water level in the hole, the third stage begins, which is the start of the controlled T profiling measurements. Initially, when the liner goes below the water level, the liner is temporarily restrained to create tension and then the liner is released to descend. The rate of water addition to the liner in this stage is carefully controlled to create a nearly constant applied head differential between the inside of the liner and the water level in the formation outside the liner. The rate at which water is added to the liner is governed mostly by the rate at which the water can escape into the permeable features in the open hole below the descending liner as it forces the water out into the permeable zones in the formation. The rate of water addition from the hose typically ranges between 0.5 and 100 L/min. Occasionally, the rate has to be larger when the transmissivity of the hole is exceptionally large. In such circumstances, the rate may reach hundreds of liters per minute. However, above such large rates, the current equipment cannot achieve the desired accuracy of measurement. If the transmissivity of the entire hole is exceptionally small, then the liner descent rate is so slow that the profiling effort is rendered impractical. However, in this case, what is learned for the profiling attempt is nevertheless valuable. An impractically slow liner descent indicates that there are no zones in the entire length of hole that have transmissivity above the detection limit, which establishes an upper bound on the bulk transmissivity of the hole. For this information to be most useful, the borehole must be well developed to clear all fractures of drill cuttings.

The static water level measured in the open hole just prior to the onset of profiling is referred to as the blended head or static water level and this is an important feature of the open-hole hydraulic system. The blended head is the equilibrium head that is achieved as a result of water flowing into the hole from those fractures that have relatively high head in the formation and water leaving the hole from those fractures with lower formation head. The inflows and outflows adjust through these vertical cross connections to produce the static blended head. In the formation away from the hole, the head distribution is governed by the groundwater flow system within the larger spatial domain. The blended head condition is a local hydraulic equilibrium and some distance away from the hole this disturbance caused by these open-hole cross connections is negligible.

To start the profiling, the water level in the liner is raised a few meters, generally between 3 and 6 m above this initial open-hole blended head to drive the liner downward. This applied head differential is referred to as the driving head. The driving head is set based on the knowledge of the initial blended head to create the necessary head differential to drive the liner down the hole. All flow of water from the hole under this condition is outward into the formation. During this period when the liner is descending down the hole, all cross connections in the hole have been eradicated. However, as the liner passes the first permeable fracture and seals it, the head in the water column below the liner may change to reflect the new condition and some change can occur continually until the liner reaches the bottom of the hole. The head below the descending liner is measured by a pressure transducer situated at the bottom of the hole. Therefore, the head in the hole below the liner is always known and is governed primarily by the applied head differential. However, extreme conditions are possible and are mentioned here to help illustrate the difference between a simple situation where the formation heads all along the hole are not greatly different and the more complex scenario of highly variable head. For example, if the bottom part of the formation around the bottom part of the hole is strongly artesian, then it would be possible that the driving head, which is set according to the initial blended head, would become so small that the liner would stop its descent. Another extreme condition could be that the formation head toward the bottom of the hole is exceptionally low and therefore in this part of the hole the effective head differential becomes too extreme that the liner ruptures. For such ruptures to occur there must be cavities or large aperture fractures into which the liner expands excessively. The actual head distribution in the formation around the open hole is not known before profiling begins; only the blended static head is known. However, insights about the head conditions are commonly obtained during the profiling procedure from system behavior and from the transducer record. Field experience with profiling many different sites shows that the two contrasting extreme conditions outlined above are not common.

To allow the data records acquired during liner descent to serve for calculation of the T profile, it is essential that the following measurements be made using the equipment setup shown in Figure 2: elapsed liner descent time, depth of the liner in the hole below top of casing at each time step, liner tension, and the head inside the liner that is measured using a bubbler tube system. This bubbler system is located in an internal sleeve in the liner to minimize disturbance by the water fed into the liner from the hose. The bubbler tube receives a constant airflow from an air tank and the system is adjusted so that the air pressure in this tube is a measure of the head inside the liner. These bubbler head measurements, along with the blended head value, allow the driving

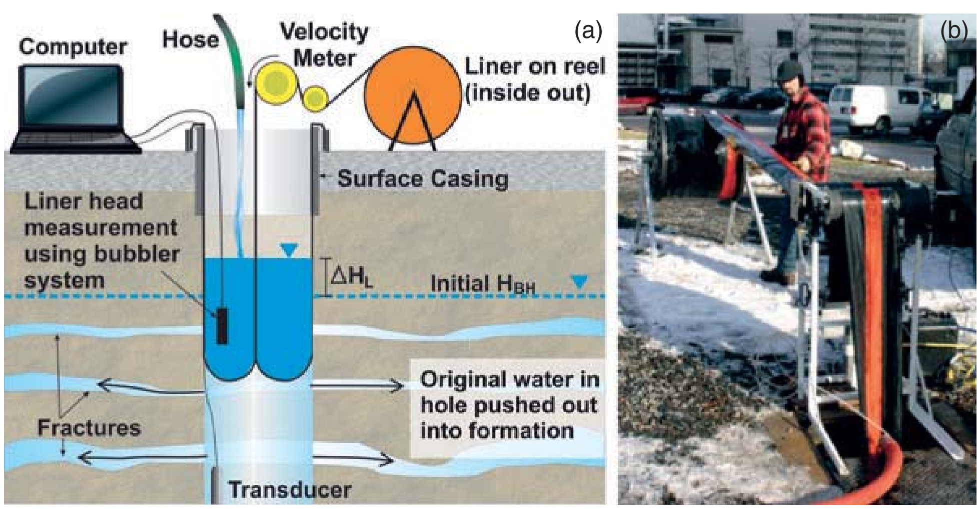

Figure 2. System components for the profiling method (a) (not to scale, vertically compressed). As water is added to maintain a constant head differential (ΔH_L) between inside the liner and the initial blended head, the liner descent rate (velocity) is measured as the head below the liner is measured (by the transducer) and (b) photograph showing the liner deployed from the shipping reel in the background and extending through the profiler positioned above the hole (foreground).

head to be calculated. The measurements of each of these quantities are made electronically at 0.5- or 1-s intervals. Other critical information that is not time dependent is also recorded including hole depth, hole diameter, casing depth, and casing height aboveground. The head in the liner is maintained constant during liner descent by adjusting the flow from the hose. The rate of descent, referred to as the liner velocity, is measured using a pair of encoders on a meter roller that accurately measures across a large velocity range. The velocity of the liner coming off the reel is measured by the roller for each time step (0.5 or 1 s), and therefore the velocity of the "eversion point" (EP) at the bottom of the liner (Figure 1c) is known because it is exactly half of the velocity of the liner entering the hole. The velocity is greatest at the beginning of the profiling when the length of open hole is longest and all permeable features along the hole are available for water escape in response to the driving head. As transmissive features are sealed off by the descending liner, the velocity slows at each transmissive feature as is explained in more detail in the next section. When the velocity slows to about 1 m/h, it is commonly decided to stop profiling measurements because of minimal continuing benefit. The T at this velocity for the remaining length of open hole is about $0.012\,cm^2/s$ for a 15-cm diameter hole. The tension in the liner during the descent is measured using a monitoring roller equipped with a braking system. This tension measurement is performed using a pair of load cells with analog data converted to digital data recorded on a laptop with each recording event. A spread sheet is used as the liner descends to calculate the depth, velocity, driving head, pressure below the liner, and the other parameters needed for data analysis.

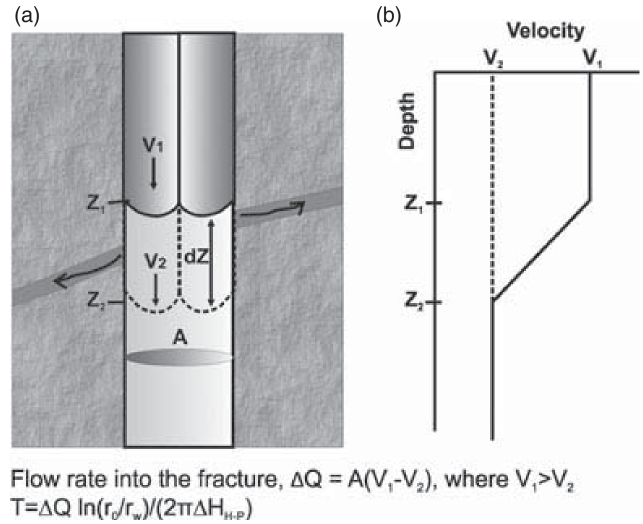

Figure 3. Schematic illustration showing the parameters involved in the measurement of transmissivity of a single permeable feature (e.g., fracture). The liner velocity changes from V_1 to V_2 as the liner passes (shuts off) a fracture over depth increment Z_1 to Z_2.

intervals (e.g., recordings made 0.5 or 1 s apart). Figure 3b illustrates the ideal case for a single fracture. The EP depth over which the drop in liner velocity occurs identifies the location of the transmissive zone. Therefore, the entire descent velocity history is governed by the distribution of the transmissive features along the borehole.

The obtained velocity profile typically shows several types of changes in shape and those commonly observed are illustrated in the hypothetical velocity profile shown in Figure 4, in which the first interval has a slope of

Identification of Transmissive Features

The capability of the liner method to provide information concerning transmissive features is based on the fact that, as the liner acting as a piston goes down the hole, the water column is pushed out into the formation through transmissive zones (transmissive fractures and other permeable features). As this happens, the rate of descent (liner velocity) changes by an amount proportional to the transmissivity of each permeable feature passed and therefore closed off by the liner. The water flow rate out of the open borehole into the formation beneath the liner is simply the velocity of the bottom of the liner (EP) multiplied by the horizontal cross-sectional area of the hole. At the beginning of the profile, the initial rate of flow is a direct measure of the transmissivity of the entire hole. Because of the constant driving head imposed inside the liner, the liner velocity must decrease each time it passes a transmissive feature because the remainder of the hole then has lower T. When the liner passes a transmissive fracture receiving flow at a rate of ΔQ (Figure 3a), the liner velocity drops by an increment equal to $\Delta Q/A$ when the EP passes the fracture, where A is the horizontal cross-sectional area of the hole. The precision of the location of transmissive zones is dependent on the time record

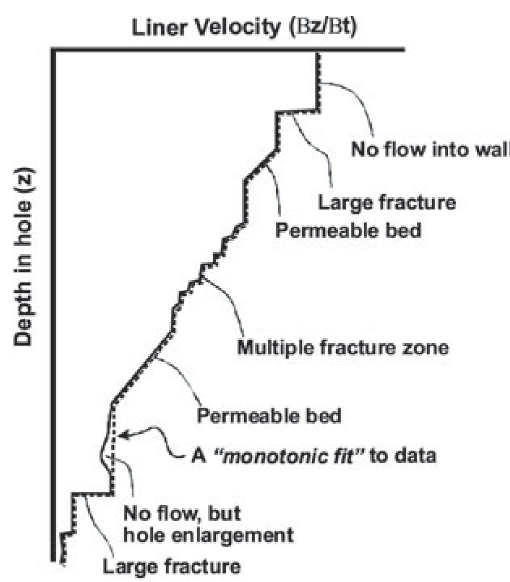

Figure 4. Hypothetical ideal "liner descent velocity profile" showing changes caused by several types of borehole features. The monotonic fitted line ignores temporary drops in liner velocity such as caused by a borehole enlargement where the liner velocity decreased but then increased upon exiting the enlargement.

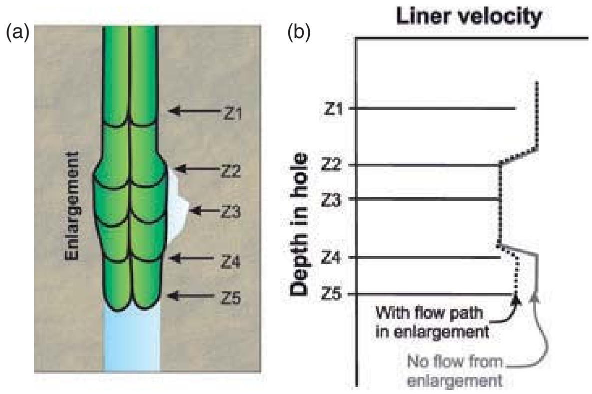

Figure 5. Hypothetical illustration of effects of borehole enlargement: (a) borehole conditions with blank line expanding where borehole is enlarged with five points along the liner, above (Z_1), within (Z_2, Z_3), and below (Z_4, Z_5) the enlargement interval, and (b) liner descent velocity profile showing an apparent temporary decrease in liner descent velocity followed by an increase after the liner passes the enlargement. In the absence of a permeable feature within the enlargement area, the liner velocity returns to the pre-enlargement rate.

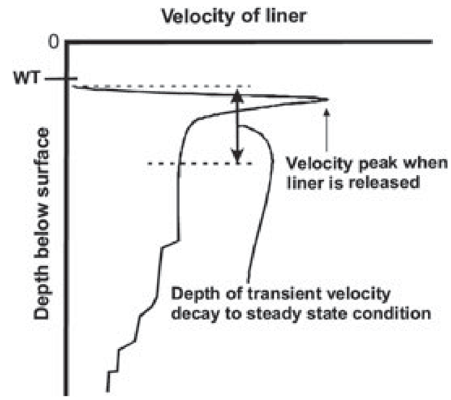

Figure 6. Transient velocity decay to steady-state conditions during early stage of liner eversion. Upon release of the liner, the liner velocity immediately peaks and then drops to the nominal steady-state flow rate. Thereafter, the velocity changes are governed by the sealing of transmissive features.

zero, representing no detectable permeability and thus no flow features in this interval being sealed by the liner. The initial abrupt step change in velocity is typical of the liner passing a thin, discrete, nearly horizontal, permeable fracture intersecting the hole. The less abrupt, sloped portions of the velocity profile indicate transmissive intervals of substantial vertical thickness. These features can have various characteristics such as a uniform permeable bed (a smooth slope) or a zone with multiple fractures (a slope composed of numerous small steps) or a fracture intersecting the borehole wall at an angle.

In addition to the transmissivity of the borehole and the driving head in the liner, other factors can influence the velocity of the liner descent. Recognition of these factors is necessary to avoid them being incorrectly interpreted as transmissive features. For example, some boreholes have intervals where the hole diameter is enlarged, known as breakout or washout zones. As the liner passes through an enlarged segment, the liner expands slightly to fill the larger cross-sectional area (i.e., a larger volume displacement per unit length of travel) causing a corresponding drop in the liner velocity (Figure 5). This drop in velocity is not caused by formation transmissivity, but could be falsely interpreted as such. In field trials, the presence of this borehole enlargement effect is usually recognized because, when the liner passes out of the enlarged zone, the liner cross section is smaller relative to the nominal borehole dimension and the velocity then increases proportionally. The decrease followed by increase in velocity is diagnostic evidence for borehole enlargement. Figure 5 shows a sequence of a liner passing through an enlarged borehole segment where the liner may not be able to expand enough to press against the enlarged borehole wall and therefore the liner in effect is a balloon in this interval of the hole. If the liner exit velocity from the enlargement is less than the entrance velocity, the velocity change, and the associated transmissivity, is assigned to the upper portion of the enlargement. Therefore, the effect of a washout or solution cavity or other enlargement of the borehole on the profile is taken into account by the fit of a monotonically decreasing curve to the data that ignores the temporary drops in velocity. In some cases, the borehole diameter is determined independently by geophysical logging (mechanical caliper or virtual caliper from acoustic televiewer [ATV] logs) before conducting the profile so that borehole diameter variations are anticipated in the profile interpretation.

In the calculation of T values from the velocity profiles, steady-state flow is assumed. However, at the start of profiling when the liner is released to propagate down the hole, a short period exists when the flow out of the borehole is clearly not steady state (Figure 6). The velocity data obtained during this transient period are not used for fracture T determinations. In this transient period, the hydraulic gradient from the borehole wall into the formation is imposed instantaneously at the beginning of a profile and is initially extremely steep as the liner descent accelerates to a peak velocity (Figure 6). As the transient flow field propagates outward in the formation, the gradient at the borehole wall becomes much less steep and both the flow rate out of the hole beneath the liner and the associated liner velocity approach a nominal steady state. Fortunately, the transition interval in the hole is usually only about 2 to 6 m long, depending upon the liner velocity, and therefore the lack of useful T data from such a short section of the hole is usually not substantial and commonly some of this interval is in the casing, not in the open hole being tested.

Framework for Calculation of Transmissivity

The Thiem method (Wenzel 1936) for radial steady flow is used to obtain T values from the profiling data for the open borehole segment remaining below the liner as the flow paths are sealed from the top downward. As the liner is driven down the hole and the velocity decreases

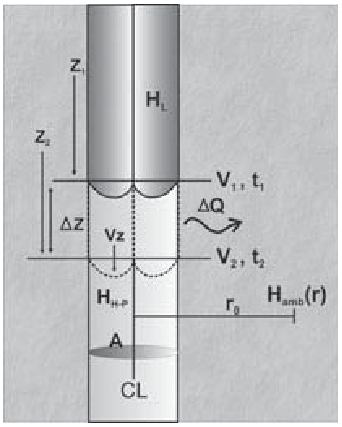

Figure 7. Diagram illustrating the parameters and concepts used for the mathematical framework of the transmissivity measurement.

as each permeable feature is sealed off, ideally, the flow rate into each fracture below the EP is nearly constant such that the flow regime in all fractures receiving water is at quasi-steady state at and near the borehole wall. The parameters used in the application of the Thiem equation for T calculation are indicated in Figure 7. The flow out of the borehole interval sealed by the liner in one time step is assumed to be steady-state Darcian radial flow represented by ΔQ. The steady-state radial condition represented in cylindrical coordinates is assumed to begin once the liner descends below the aforementioned transient interval early in the profiling. Therefore, there has been substantial time available for a steady-state flow to be achieved. This use of the Thiem equation presented here has general similarities to its use for calculating T values from constant-head packer test results in fractured rock holes as described by Maini (1971), Haimson and Doe (1983), Braester and Thunvik (1984), Lapcevic (1988), Novakowski and Bickerton (1997), and others. Quinn et al. (2012) provide a summary of the Thiem method applied to straddle-packer tests. For both liner profiling and packer testing applications, the Thiem equation is expressed as

$$T = \frac{\Delta Q}{2\pi \, \Delta H_{\text{H-P}}} \ln\left(\frac{r_0}{r_w}\right) \tag{1}$$

where ΔQ [L^3/t] is the flow rate reduction due to sealing an interval of the borehole, T [L^2/t] is the transmissivity of the portion of the borehole measured ($K\,\Delta z$), $\Delta H_{\text{H-P}}$ [L] is the applied head difference in the borehole above the open-hole blended head, r_0 [L] is the radius of influence of the test, and r_w [L] is the radius of the borehole.

As with all single-well tests, the r_0 cannot be measured and therefore an assumed value is used. In packer testing literature for fractured rock, assumptions of r_0 ranging from 10 to 60 m have been justified (e.g., Maini 1971; Haimson and Doe 1983; Bliss and Rushton 1984). However, because the T may vary over several orders of magnitude, the uncertainty caused by the r_0 value selection is small as it is contained in the natural log term. This uncertainty is generally not viewed as important when the Thiem equation is applied to straddle-packer test results because the T values from such tests are generally referred to as "order of magnitude" estimates (e.g., Maini 1971; Ziegler 1976; Haimson and Doe 1983; Bliss and Rushton 1984; Lapcevic et al. 1999). For this study, $\ln(r_0/r_w)$ is set to a value of ln(600) representing a 30-m radius of influence in a 100-mm (4-inch) borehole, which is the value recommended by Haimson and Doe (1983) and used by Quinn et al. (2011a, 2011b, 2012) for calculation of T values from constant-head packer tests in the Guelph dolostone aquifer. In application of the Thiem equation to straddle-packer test results, the r_0 value is generally fixed at the same value for all tests in each hole and for many holes at the same site, even though the extent of radial influence must vary in some unknown amount from interval to interval because of different injection rates and fracture apertures.

The preferred method for obtaining the actual head in the water column in the hole below the descending liner, $\Delta H_{\text{H-P}}$, relies on a transducer, such as a Solinst Levelogger model 3001 or a Schlumberger Diver positioned at the bottom of the hole with on-board recording and transmission of the pressure history to the surface via a slender cable (Figure 2). This downhole transducer allows continuous recording during profiling of the head driving the water into the formation. For lower cost and/or to avoid the potential of any leakage along the cable, a self-contained version of these recording pressure transducers attached to a thin string (e.g., fishing line) can be used. However, when a transducer attached to a string is used rather than a transducer attached to a data transmission cable, the data are only available when the transducer is retrieved after the liner is removed. This is not ideal when the plan is to leave the liner in place to seal the borehole for longer periods.

This method of using the FLUTe liner as a piston to obtain velocity profiles is referred to as a transmissivity (T) profiling method rather than a hydraulic conductivity (K) profiling method because conversion from T to K requires exact knowledge of the vertical interval across which the flow has occurred. The interval of measurement depends on the measurement recording frequency. Because the velocity decreases as profiling proceeds, the interval of measurement decreases with depth. Therefore, because the velocity is measured and time intervals are known, which provide the interval for each T calculation, K can be calculated as an average for each interval.

Estimation of Head Below the Liner

For avoidance of transducer use, borehole pressure beneath the liner is estimated using an empirical equation derived from laboratory tests of liner tension vs. driving pressure during liner eversion and inversion:

$$H_{\text{H-P}} = \Delta H_{\text{L}} - H_{\text{MIN}} - \frac{2\,(\Theta_w + \Theta_D)}{A} \tag{2}$$

where ΔH_L is the driving head in the liner, H_{MIN} is the minimum head needed to evert the liner against the resistance due to the fabric stiffness, Θ_w is the recorded tension on the liner at the wellhead, Θ_D is the total drag force on the liner within the borehole (friction), and A is the borehole cross-sectional area. The factor 2 is an empirical coefficient determined from many eversion tests in a laboratory apparatus using different liner materials. The tension at the wellhead (Θ_w) and the head inside the liner (H_L) are precisely measured in the field while profiling using load cells selected for the desired load range and a pressure transducer mounted in the profiler, respectively. The total drag on the liner (Θ_D) is not measured, but is intentionally reduced to as near zero as possible. The drag term becomes important when the water table is very deep or when profiling a borehole with extremely high transmissivity. For profiling in boreholes with deep water tables, the use of a tremie hose inside the liner to introduce the water at the water table depth without wetting the inverted liner helps to minimize the drag. In extremely high-permeability boreholes, the driving head in the liner (ΔH_L) is kept as large as possible to reduce the significance of drag on the liner. Uncertainties in Θ_w, Θ_D, and the "factor 2" are only significant to $\Delta H_{H\text{-}P}$, and therefore T, to the extent that the uncertainties are large relative to ΔH_L. For that reason, it is important that ΔH_L be relatively large, but not so large as to rupture the liner. It is also important that the head in the hole beneath the descending liner, $H_{H\text{-}P}$ in Figure 7, exceeds the head everywhere in the formation so that all flows are out of the borehole and that there is no cross flow occurring in the borehole between transmissive intervals. Significant inflow is easily recognized in that it causes an increase in the velocity, violating the expectation of a monotonically decreasing liner velocity. Comparison of the calculated head from surface measured parameters with the directly measured head beneath the liner generally shows excellent agreement as indicated by the example shown in Figure 8, which is typical for the many holes where this comparison has been made.

The velocity per unit driving pressure ($v_i/\Delta H_{H\text{-}P}$) for each time step is plotted vs. depth to create a velocity profile of the borehole. Because the depth increments for each time step vary with the liner velocity, the hydraulic conductivity obtained from the transmissivity calculation has variable depth resolution. The largest intervals (Δz_i) are located at the top of the borehole where the velocity is highest. Changes in the velocity per unit driving pressure are then calculated throughout the borehole and multiplied by the borehole cross-sectional area to obtain $\Delta Q/\Delta H_{H\text{-}P}$ for use in the Thiem equation.

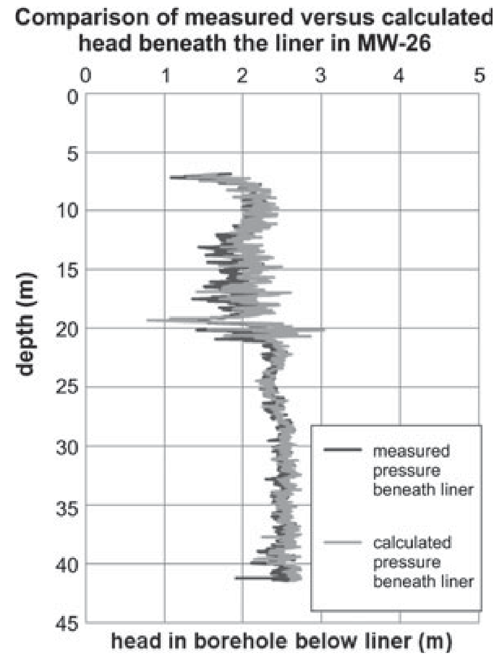

Figure 8. Comparison of measured pressure history from the transducer at the bottom of the hole beneath the liner with the calculated pressure history using the measurements of the liner at the surface for MW-26. In this case, the agreement is very good and the transmissivity results are essentially the same using either history for this borehole. Boreholes with higher vertical flow rates (>38 L/min [10 gpm]) generally do not show such good agreement.

Insights from the Velocity Profile

Profiling results from three holes in the Guelph fractured dolostone aquifer are used here to illustrate insights derived from the liner profiling method. The overburden at the site is between 3 and 5 m thick. Boreholes were continuously cored (HQ, 96-mm diameter) from the top of rock to the bottom of the boreholes up to 100 m below-ground surface (bgs). The water level in the open boreholes varies seasonally between 3 and 5 m bgs. This dolostone aquifer supplies most of the municipal water supply for the City of Guelph. Borehole flow metering in open unpumped holes shows that some boreholes in this formation have downward vertical flows greater than 400 L/min. This flow condition is caused by the pumping of municipal wells that draw most of their water from the deep part of the aquifer. The three boreholes were selected to show the nature of velocity profiles. In 2006, the liner method was applied twice in 1 d in borehole MW-24, which extends through the full depth of the 100-m-thick dolostone aquifer into the underlying shale aquitard. Each profiling episode took about 2 h. In the first step of liner profiling data processing, the data from each run were smoothed, as shown in Figure 9a, to produce a velocity profile used for hydrogeological interpretation. The profile smoothing process removes the small oscillations in the profile reasonably attributed to noise caused by the measurement and recording devices. Figure 9a shows both the raw velocity profile and smoothing results for MW-24, with the profile smoothed over three successive time steps and the monotonic fit of the smoothed curve. The degree of smoothing needed is judged by the amount of deviation from the raw data. For this example, the excellent match of the three profiles is typical of what is deemed to be a "good data set."

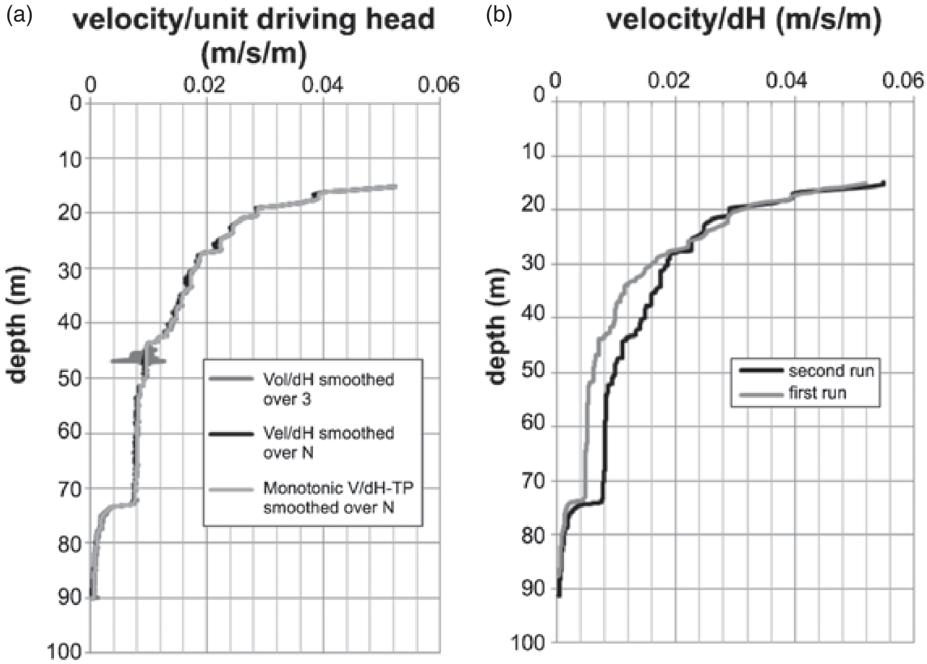

Figure 9. Plots showing (a) data from MW-24 liner profiling showing raw and smoothed velocity profiles over three time steps (6 s) and monotonic fit used for hydrogeological interpretation, and (b) monotonic fit for two profiling events done on the same day, showing generally similar results but with the *T* obtained in the zone of the most prominent permeable feature at 73 m bgs greater from the second run, which is attributed to "well-development" effects caused by liner removal after the first run.

An unexpected benefit of the liner method is its use for removing sediment clogging from fractures. Figure 9b shows the monotonic fit for the two profiling events done on the same day. The two profiles are generally similar, but the T obtained from the second run was greater than the first by about 60% at the most prominent fracture at 73.1 m bgs. This difference is likely owing to "well-development" effects caused by the removal of the liner after the first run. A specially designed machine referred to as a "linear capstan" is used to remove the liners as quickly as possible by applying strong tension to the tether that is attached to the bottom of the liner causing the liner to invert back up through the borehole. This tension creates a strong low pressure beneath the liner that draws water from the formation into the borehole. The tension typically applied produces a pressure drawdown estimated at up to 30 m of head difference between the water column in the hole and the formation pressure represented by the open-hole blended head. This large inward hydraulic gradient promotes removal of sediment clogging fractures. This increased transmissivity (and corresponding decrease in liner profiling time) has been observed in other boreholes where a blank liner was removed and installed a second time.

In boreholes that penetrate through an aquifer into an aquitard, the liner method provides insights about the nature of the contact or transition between the aquifer and the aquitard. This is illustrated by the liner profiles in MW-24 (Figure 9b), which show strongly decreasing velocity in the first 35 m gradually becoming slower with an abrupt velocity drop at 75 m bgs. The profiling was discontinued at 93 m when the velocity became so slow that there was no further benefit to continuing the measurement. The point at which the liner descent velocity became markedly slower indicates that the horizontal transmissivity below this elevation is much smaller than above. However, the contact with the aquitard is at 102 m bgs, where the shale begins as indicated by core and gamma logs. Figure 10 shows the T profiles in this hole alongside other types of borehole information. The depth (~93 m bgs) at which liner descent velocity detected minimal transmissivity, and therefore only slightly permeable fractures, coincides with the depth (~92 m bgs) below which no active groundwater flow was detected by Pehme et al. (2010) using high-resolution temperature profiling in the water column in this lined hole.

The liner profile expressed as T (Figure 10e) shows numerous transmissive features. It is reasonable to attribute each drop in velocity to a permeable fracture or fracture zone because the rock matrix permeability, as indicated by laboratory tests of representative core samples is small, about 5×10^{-9} m/s. This is a factor of 100 lower than the practical limit of liner measurements; therefore, the features identified by this profiling method are due to individual fractures. However, one must be wary of inferring too much about the transmissivity ascribed to each small interval traversed in a time step as an individual fracture. An obvious example is that near the bottom of the hole the liner is moving at less than a centimeter per half second time step. If a high angle fracture intersects the

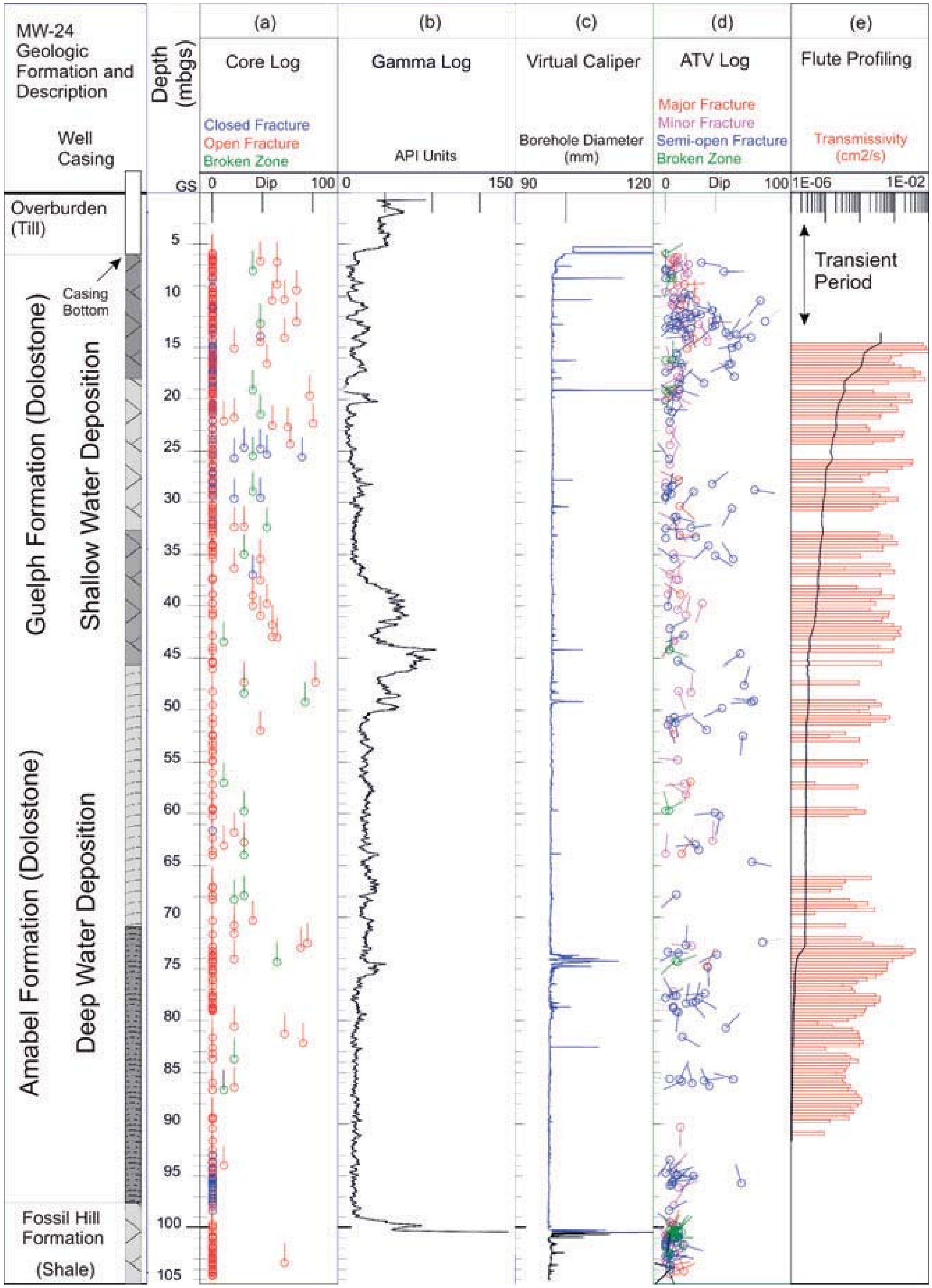

Figure 10. Geological and geophysical features in MW-24 displayed along the liner *T* profile. The core log, caliper, and ATV logs all indicate the presence of numerous fractures, which is consistent with the liner profile where the *T* values are integrated over 1-foot intervals.

borehole over a vertical distance of 20 cm, the liner measurement will divide the sealing of that fracture into about 40 time steps corresponding to 40 velocity increments which sum to the total velocity change as the liner seals the single fracture. Likewise, at the top of the hole, the liner may pass several fractures in a single time interval at a higher velocity. The continuous curve of Figure 10e is the integral of the transmissivity from the bottom of the hole to the top. The step changes in the curve are visually correct for the relative magnitude of each flow zone. The bar graph of Figure 10 is the integral of the discrete transmissive intervals over a fixed interval of 0.30 m. This would be comparable to a continuous series of 0.3 m straddle-packer tests. Such a short interval allows the easy identification of the prominent transmissive features. A shorter interval of integration would perhaps define the individual fractures more clearly. However, at some small scale, the inherent noise in the measurement would lead to very small false fractures.

Figure 10 shows that the liner profiling indicating numerous transmissive features is consistent with the occurrence of large numbers of fractures in this hole inferred from inspection of continuous rock core and acoustic televiewing. It is also consistent with the high-resolution temperature profiling inside the lined hole by Pehme et al. (2010), which showed a total of 18 hydraulically active fractures between depths of 34 and 91 m bgs. Above 34 m, the temperature profiling method did not provide data suitable for fracture identification. The core log and ATV identified fractures, but provide no indication of whether these fractures are permeable or not. It is reasonable to expect that the total number of significant fractures identified by the liner profiling method can be larger than the number identified by high-resolution temperature profiling (Pehme et al. 2010) because not all permeable fractures would have the degree of active groundwater flow needed for identification using only temperature profiles. For some fractures, the sensitivity for identification of fracture position or presence using the profiler method will be lower than the temperature method.

Comparison to Straddle-Packer Results

Packer testing was done at 1.5-m intervals throughout the full length of two holes (MW-26 and MW-367-7) in the Guelph dolostone aquifer using the constant-head injection step method. Quinn et al. (2011a, 2011b) describe the equipment and test procedures applied in these holes. Figures 11 and 12 show comparisons of T profiles from the liner method with measurements from straddle-packer tests. The liner profiles provide T values due to permeability offered by individual fractures or specific intervals with multiple fractures or solution channels. It was necessary to integrate the liner measurements for comparison to the packer results by summing the liner T values over the same 1.5 m intervals as the packer test profile.

The depth-integrated (1.5 m interval) T profiles from the liner profiling of holes MW-26 (Figure 11) and MW-367-7 (Figure 12) are very similar to the packer testing results, except for the uppermost part of the hole where, as expected, the transient period prevented determination of T values from liner measurements. In the part of the hole where both methods gave T values, most intervals have similar values. The liner profile does not resolve transmissive features less than approximately 1% of the remaining transmissivity beneath the liner. For that reason, some of the lowest packer test values correspond to no measured transmissivity for the liner profile. There is a small tendency for packer testing T values to exceed liner T values in the bottom half of the hole, which is consistent with the expectation that the liner method has best accuracy toward the bottom of the hole, and the expectation that the liner method is prone to underestimate T values because of the effect of non-Darcian flow. The packer testing method used in these holes (Quinn et al. 2011a) was directed at avoiding errors as a result of non-Darcian flow, as discussed in the next section.

The liner profiling method provides the T for the entire hole below the point at which the transient condition ceases, which comes from the velocity measured at this point. For MW-26 and MW-367-7, these liner T values were 1.1 and 1.3 cm^2/s, respectively, which are close to the T values obtained for the same sections of these holes by totaling the packer testing values, which provided 1.0 and 1.5 cm^2/s, respectively. The closeness of these "entire hole" T values illustrates use of the liner profiling method as a rapid means for determining entire hole T values. The closeness of these values suggests that although the two methods have different sources of error and uncertainty, these are not so large as to cause the T values to differ substantially from total aquifer thickness or hydrogeologic unit perspective.

The liner profile in MW-26 (Figure 11) has two gaps where the intervals are below detection, and one gap in MW-367-7 (Figure 12) where the packer testing also showed relatively low T values. These below-detection gaps occur in the upper part of the hole above the highest T intervals, which occur in the middle of these holes. This is also consistent with lesser liner method sensitivity in the upper part of holes. Nonetheless, the overall assessment through comparison of the two methods in these holes provides confidence that liner method T profiles provide good estimates compared with carefully performed straddle-packer tests, and that the profiles are a reasonable representation of the hydrogeologic conditions in the holes based on multiple lines of evidence.

Difficult Conditions, Limitations, and Uncertainties

The liner profiling method is aimed at providing two types of information: (1) positions of permeable features along the borehole and (2) transmissivity estimates of permeable features along the borehole wall. A permeable feature may be a single fracture, a solution channel, an interval with numerous closely spaced fractures, or in some cases a zone where there is substantial rock matrix permeability. There are reasons for evident errors or uncertainties associated with the liner results for each of the two types of information. As the liner descends into the hole, the descent rate is measured at set time intervals (e.g., every half second). The applied head inside the liner is maintained by adjusting the rate at which water is added to achieve a constant positive differential between the head inside the liner and the head outside the liner in the formation. The liner descent rate (velocity) decreases each time a permeable feature is sealed by the passing liner. Because the descent rate is measured at a set time interval and the descent rate diminishes down the hole, the resolution based on the

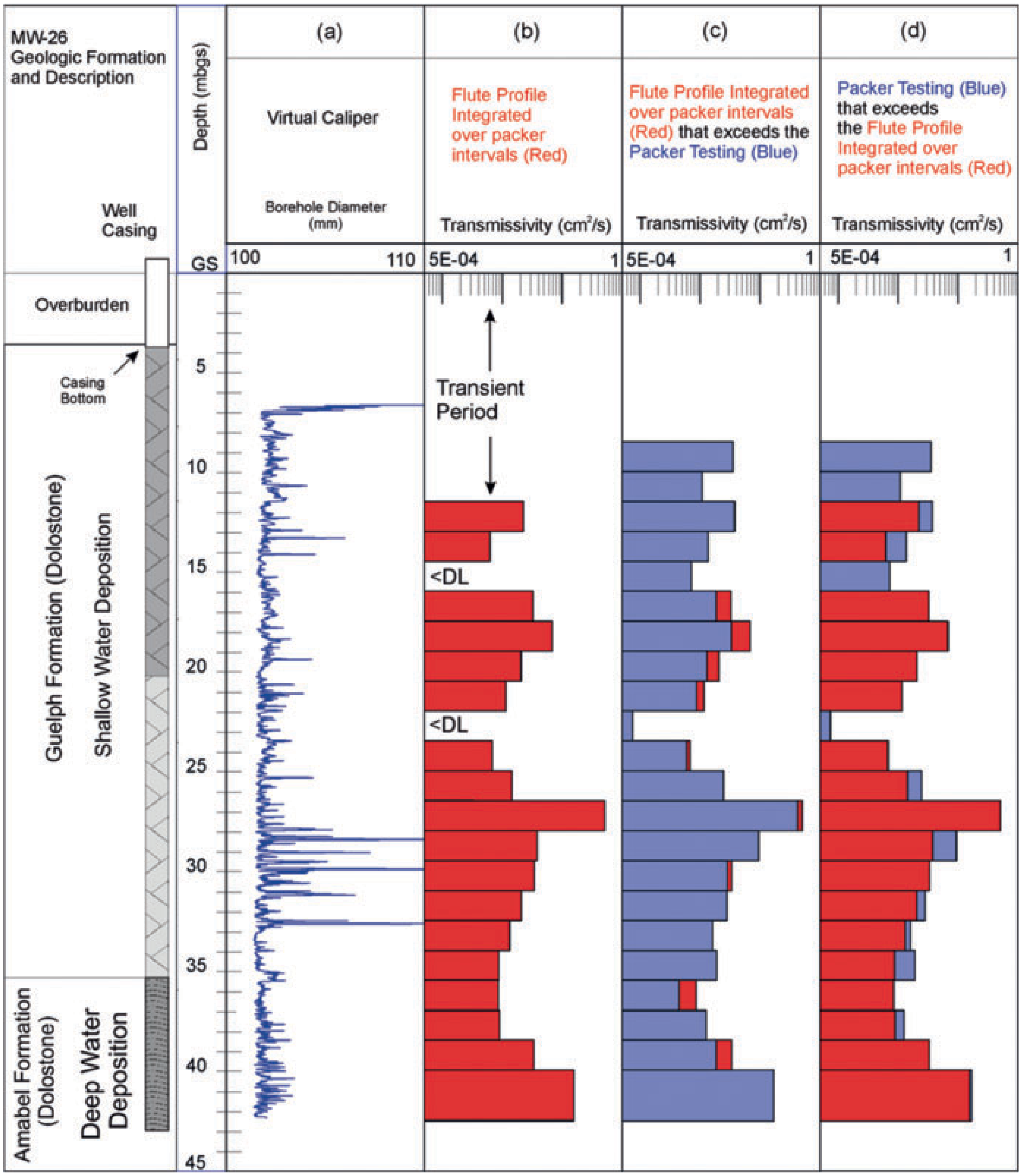

Figure 11. Comparison of liner T profile with packer test T values in MW-26. The raw FLUTe profile integrated over the packer intervals is shown in column (b). The integrated FLUTe profile is compared to the packer testing values in columns (c)-(d). Column (c) shows the intervals in which the FLUTe had a larger value for T, and column (d) shows the intervals where the packer testing had a larger value for T. Geology and well construction are shown to the left of the diagram, and column (a) shows the virtual caliper log of borehole diameter.

descent rate measurements increases with depth down the hole; and therefore the sensitivity of the liner profile to detect permeable features increases down the hole. The highest resolution of transmissive feature identification is achieved in holes where the highest transmissive zones are nearest to the top of the hole rather than at the bottom of the hole. Fortunately, at many sites the highest T zones occur at or near the top of rock where there has been more weathering or structural disturbance. In holes where the highest T is at or near the bottom of the hole, features with relatively much lower T go undetected.

Regardless of the distribution of permeable features along the borehole, the liner profile is normally expected to provide a reliable measurement of the total transmissivity in the open hole beneath the initial transient interval and it is generally very unlikely that the liner profiling method will miss identification of any major transmissive features. Cumulative experience obtained from profiling many different hydrogeologic settings indicates that the only holes where the velocity was too fast to obtain useful T was in karst with large solution channels near the bottom of the hole. The fastest profile to date was to 71-m

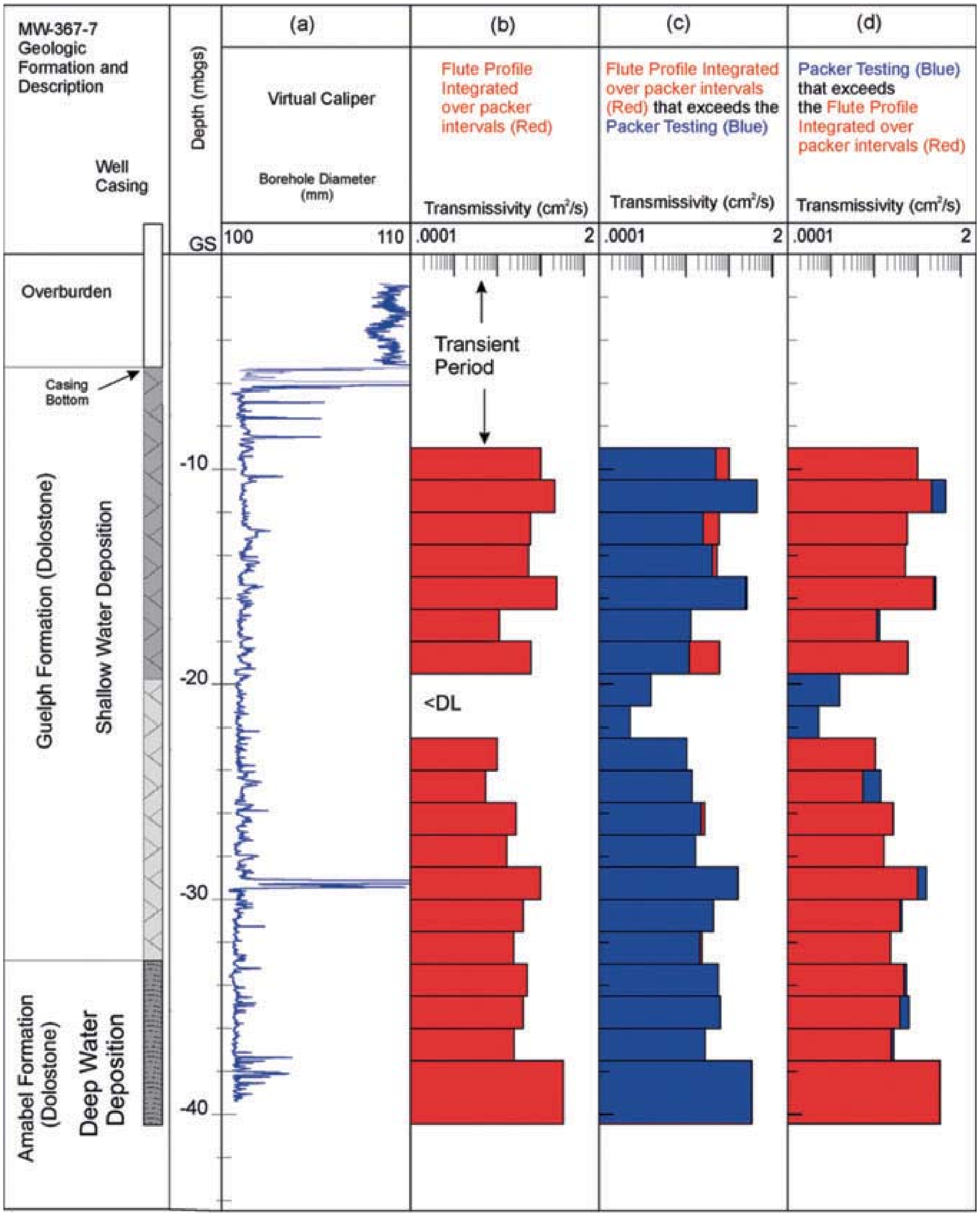

Figure 12. Comparison of liner T profile with packer test T values in MW-367-7. The raw FLUTe profile integrated over the packer intervals is shown in column (b). The integrated FLUTe profile is compared to the packer testing values in columns (c)-(d). Column (c) shows the intervals in which the FLUTe had a larger value for T, and column (d) shows the intervals where the packer testing had a larger value for T. Geology and well construction are shown to the left of the diagram, and column (a) shows the virtual caliper log of borehole diameter.

depth in 12.5 min and the spatial resolution of this profile was poor. However, profiling has also provided many useful profiles in karstic rock environments.

Artesian conditions present a particular but not insurmountable challenge. In a few cases where liner measurements were desired and the static head in the hole was above-ground surface (i.e., flowing artesian hole), the liner method was difficult but found to be feasible when a temporary structure (e.g., scaffolding) was used to allow application of the head differential necessary to drive the liner down the hole. Recently, a more sophisticated approach for artesian holes has been applied that uses an attachment to the top of the wellhead to enable pressurization.

A much different problem arises in boreholes where a large inflow of cascading water occurs from a shallow fracture located in the exposed borehole segment above the blended head. This condition can exist only where there is a high-T, low-head zone deeper in the hole. Profiling in these holes can be difficult or impossible. The cascading water has a tendency to pull the liner into the borehole without applied head, and the high flow along the borehole wall may prevent proper sealing. In one hole, this problem was avoided by feeding an extremely large flow rate (e.g., 400 L/min) into the liner to keep the driving head large enough to seal the shallow inflow zone. Excessively high head may occur at some depth in the hole even though the blended head is not exceptionally high. In such cases, the liner profile may show no apparent transmissivity at this excessively high head zone, but when the liner passes the inflow zone and seals it, the liner descent velocity increases to compensate for the lost inflow. To confirm this excessive head condition, once the liner is in place, the water level can be lowered inside the liner in successive steps. When the water level no longer drops with the water removal, the head in the liner is at the highest head in the formation, because that highest head interval is starting to collapse the liner. Identification of these artesian intervals in this manner is very useful to the design of multilevel liner systems. Flowmeter measurements can also be useful evidence of this condition.

Although application of the Thiem equation for calculation of the T values is most appropriate, this can be a source of T value uncertainty because of differences between the actual field conditions and those assumed in the derivation of this equation. The Thiem equation is based on the assumption of steady-state horizontal flow in a fully confined horizontal layer (Todd 1980). The steady-state assumption is most appropriate because, typically, the borehole has been open for many hours or days before liner profiling begins. Because of cross connection caused by the open hole, water flows into the hole from one or more fractures and out of the hole from others to establish a local open-hole, quasi-steady-state flow condition. Then liner profiling quickly imposes a new quasi-steady-state condition on the borehole. Once the liner is below the transient interval, the applied head pushing the water out of the hole into the formation is maintained as a constant differential relative to the initial blended head. This condition ensures that the flow rate (ΔQ) out of the hole at each permeable feature is constant until the liner passes and seals the feature at which point the ΔQ into the fracture goes nearly instantaneously to zero. Therefore, at each instant as the liner travels down the hole, the flow regime in the fractures above the liner bottom becomes transient as groundwater flow in the fracture network adjusts to the imposition of the borehole seal. However, below the descending liner, there is quasi-steady-state flow into each fracture because the constant applied head differential initiated when profiling begins. If the fractures are primarily horizontal with minimal vertical hydraulic conductivity, then it is reasonable to expect that the descending interface (transition zone) between the transient- and steady-state flow regimes does not influence the accuracy of the values calculated from the Thiem equation. However, in systems where there are numerous vertical or angled fractures allowing substantial vertical flow, the transient regime adjacent to the sealed hole rather than the assumed steady flow can introduce a source of error until that flow path has been sealed, at which time the total change in flow out of the borehole due to that flow path is correct. The complication of vertical flow for use of the Thiem equation also exists for straddle-packer tests where it can lead to connection of the straddled interval to the segment of open hole above and or the segment below the packers. This effect caused by vertical fractures is a form of local short circuiting. However, in profiling, this source of error is less, because the connection to the open hole above the bottom of the liner is not possible as the entire hole is sealed above the end of the liner.

There are other sources of error related to assumptions in the Thiem equation. The assumption that the initial blended head in the borehole is the same as the formation head has some uncertainty associated with it. However, this profiling method does allow the estimation of the actual formation pressure using a stepwise procedure for the liner when it is to be removed. This new technique of performing a vertical head profile during the liner removal is currently being tested to be reported in a future article. For holes where a multilevel monitoring system is installed later, the head data then obtained can be used to refine the profiling T results. Quinn et al. (2011a, 2011b) show that straddle-packer testing in these and other boreholes in the Guelph dolostone conducted at excessively large injection rates produces "non-Darcian" flow and therefore the T values are underestimated. The packer test T values in columns (c) and (d) in Figures 11 and 12 were obtained for "Darcian" flow regimes because the injection rates were controlled to achieve Darcian flow in each test interval (Quinn et al. 2011a, 2011b). However, in liner profiling, it is not feasible to control injection rates to achieve "Darcian" flow; thus, "non-Darcian" flow can be a source of error in the T values. However, based on the comparison between liner profiling and packer testing results for MW-26 and MW-367-7 shown in Figures 11 and 12, this source of error in these holes is very small. The errors in the values attributable to non-Darcian flow and the r_0 assumption are expected to generally be less than an order of magnitude.

Conclusions and Implications

Generally, the most important reason for installing liners in rock boreholes at contaminated sites is to minimize hydraulic cross connection and the associated cross contamination that is difficult to remove. However, only minimal additional effort, time, and expense are required during the liner installations to perform measurements to discern positions of permeable features and to obtain T estimates for these features. Therefore, since the introduction of this liner profiling method in 2003, it has rapidly become recognized as a useful addition to many fractured rock investigations. Testing the method in hundreds of boreholes in different hydrogeologic conditions has produced many refinements in the equipment and procedures and there is continual improvement to the method. In cases where the borehole penetrates through an aquifer into an aquitard, this method provides insights concerning the position and nature of the aquifer/aquitard contact.

Prior to the development of the liner profiling method, hydraulic testing using straddle packers was the primary method available to obtain such depth-discrete, *T* profiles in boreholes. However, except at research sites, high cost generally prevents application of comprehensive packer testing using short intervals along the entire borehole length. Therefore, in conventional contaminated site investigations, straddle-packer tests are typically done in only a few intervals in each borehole. Our experience shows that the efficacy of straddle-packer hydraulic tests is enhanced when used in combination with liner profiling, particularly when the packer tests are done after the liner profiling so that the profiles can be used to guide selection of the packer test intervals. In boreholes where the sensitivity of the liner method is minimal in the upper part of the hole because of a relatively high transmissive zone in the lower part of the hole, straddle-packer tests can be used to measure *T* values in the intervals where the liner method detects only larger fractures. Not every small drop in the monotonic fit curve is a reliable identification of a small fracture, but the sum of all the transmissive features is a reasonable estimate of the transmissivity of the borehole. As experience is gained through use of the liner profiling method and with comparisons to *T* values obtained by other methods, we can expect that the data interpretation procedure will improve.

The liner profiling method is an important addition to the group of techniques used for examining the hydrogeologic features of boreholes and offers the greatest potential for enhanced insights when used in combination with straddle-packer hydraulic tests and borehole geophysics, including temperature profiling in the holes after the liner is installed (Pehme et al. 2010, 2013). The exploration into the rigorous use of liner profiling in combination with these other methods is in its early stage.

This profiling method is an efficient means of measuring *T* profiles in some types of holes for which straddle-packer testing is not practical, such as holes where the borehole wall is unstable rock or where the rock is so highly fractured that strong short circuiting during packer tests is unavoidable. Another situation where the profiling method is exceptionally efficient and cost-effective relative to packer testing is for boreholes of very large diameter (e.g., >250 mm, 10 inches) because use of such large-diameter packers is commonly problematic. In contaminated site investigations where minimization of cross contamination between different levels in the borehole is mandatory, or at least desirable, the profiling method done soon after drilling the hole is completed occurs quickly as part of the borehole sealing procedure, whereas packer testing to measure *T* is done at the expense of cross connection.

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